A DIGITAL CONTROL SYSTEM FOR OPTIMAL OXYGEN TRANSFER EFFICIENCY

PIER FINAL PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

A Digital Control System for Optimal Oxygen Transfer Efficiency is the final report of the Development and Demonstration of Digital System for Control and Monitoring of Oxygen Transfer Efficiency Measurements project (contract number 500-03-001) conducted by Southern California Edison, the University of California, Los Angeles, and Utility Technology Associates. The information from this project contributes to PIER's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916 654 5164.

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Abstract

Aeration (treatment with air) is the most energy-intensive operation in municipal wastewater treatment. To improve oxygen transfer rate, fine-pore diffusers (air dispensers with small pores for releasing small air bubbles) have been widely applied in aeration. However, during operation, this type of diffuser suffers from fouling and scaling problems, leading to rapid decline in performance and significant increase in energy costs. Diffusers must be cleaned periodically to reduce energy costs, and cleaning frequency varies according to the reduction of oxygen transfer efficiency with time in operation. Off-gas testing (measuring the oxygen content in gas released by treated wastewater, developed by Redmon et al., 1983) is the only technique that measures real-time oxygen transfer efficiency. However, the complexity and cost of operation are preventing wide-scale installation of off-gas monitoring equipment in wastewater treatment plants. This project developed a low-cost, easy-to-operate instrument to monitor oxygen transfer efficiency and provide guidance for calculating energy consumption and waste. This instrument is auto-calibrated, and its operation does not require trained experts. The project also analyzed results of real-time monitoring in several full-scale treatment plants to demonstrate the benefits of cleaning and predict cleaning frequency. This project has the potential to allow energy savings in the range of 100 million to 150 million kilowatt hours per year in California.

Executive Summary

Background

Wastewater treatment is an energy-intensive process, and more than 50 percent of the energy used in the treatment process is spent in aeration. Cleaning aeration diffusers can reduce that energy consumption. However, proper timing of diffuser cleaning varies according to reductions in oxygen transfer efficiency—a metric that has been difficult and costly to measure.

Purpose

This project developed and tested an automatic, low cost, and simple-to-operate device that lets treatment plant operators monitor the oxygen transfer efficiency of dissolved oxygen in wastewater. Proper control of the oxygen transfer efficiency can help plant operators to determine when diffusers of aeration equipment need cleaning—a measure that can significantly reduce aeration energy consumption.

Objectives

- Develop a low-cost, easy-to-operate off-gas analysis instrument that can provide significant energy savings by allowing treatment plant operators or instrument technicians to measure the oxygen transfer efficiency of fine-pore diffusers.
- Provide oxygen transfer efficiency measurements in a simple fashion through a computer interface to a Windows® computer.
- Test the instrument in real-time in working wastewater treatment facilities.

Approach

To achieve the main goals of this project, prototypes of off-gas analyzers were built. The first step was to assemble a laboratory-scale apparatus with precise and accurate measurements for a wide range of measuring scales, thus allowing fine-tuning, debugging, and sensitivity analysis. This laboratory analyzer, because of its sophistication, was rather costly and bulky. However, this apparatus provided the basis for designing, calibrating, and testing several versions of portable, lightweight, and low-cost prototype units that were used in field testing and evaluations.

Simultaneously, the team conducted an independent assessment of the oxygen transfer efficiency and the off-gas measurement method. This assessment identified the problems associated with aeration; examined monitoring technologies available for aeration control; provided a critical review of the oxygen transfer efficiency technology and its potential benefits; and made recommendations.

To increase the value of the analyzer to the wastewater industry, two additional tasks were undertaken: a market assessment of the technology for adoption by the wastewater industry and providing technology activities such as an assessment of blower efficiency.

Technology transfer is this project's centerpiece for education and training of wastewater management and operational personnel for adoption of this technology. For this project, two workshops were conducted, one in Northern California at the Pacific Gas and Electric Energy Center in San Francisco and the other at Southern California Edison's Customer Technology Applications Center. In addition, the project team published and presented papers at major water and wastewater symposiums.

Outcomes

This project developed a low-cost, easy-to-operate instrument to monitor oxygen transfer efficiency and to provide guidance for calculating energy consumption and waste. This instrument is auto-calibrated, and its operation does not require trained experts. In addition, experiment results of real-time monitoring in several full-scale treatment plants were analyzed to demonstrate the benefits of cleaning and to predict cleaning frequency.

The testing campaign, combined with conference presentations, gave this project valuable exposure to the wastewater industry. Project results were presented at the following events:

- The California Water Environmental Association Conference in Ontario, California in March 2007.
- The International Water Association Efficient Use and Management of Urban Water Supply Conference in Jeju, Korea, in May 2007.
- The International Water Association 4th Leading-Edge Conference on Water and Wastewater Technologies Conference in Singapore in June 2007.
- As at keynote lecture at the Consortium for Energy Efficiency Workshop in Long Beach, California, in January 2007.

Conclusions

Although significant energy savings can be realized with the commercial deployment of this product, education and training of wastewater management and operations personnel are essential for broad acceptance and application.

Recommendations

- Educate and train wastewater management to increase acceptance.
- Publish results from initial testing at several wastewater facilities to demonstrate the simplicity and ease of the off-gas monitoring operation as well as the benefits of routine oxygen transfer efficiency measurements.

Benefits to California

This project has already provided several benefits to California. Five treatment plants in Northern and Southern California were tested and have already adopted corrective measures to minimize energy losses. Moreover, then numerous presentations gave this project valuable exposure to the wastewater industry. Several individuals belonging to organizations outside California have approached the project team, inquiring about the availability of the analyzer and volunteering their facilities for further testing. The Consortium for Energy Efficiency

offered to support the technology transfer by distributing all the information regarding this analyzer to their subscribers nationwide.

After the project is completed and the aeration efficiency analyzer is commercially distributed throughout California, there will be a clear advantage for California to set the standard for energy efficiency for wastewater treatment. Moreover, there is a potential opportunity for California businesses to take part in the following phase of the project, that is, manufacturing and distribution of the analyzer to the wastewater industry. Furthermore, and most important, the large-scale implementation of aeration efficiency monitoring will allow energy savings potentially in the range of 100 million to 150 million kilowatt hours (kWh) per year in California.

1.0   Introduction

1.1.   Background and Overview

Wastewater treatment is an energy intensive process. Aeration is a necessary operation for running the activated sludge process (ASP). Aeration costs account for a large fraction of a wastewater treatment plant (WWTP) expenditure. Because of aeration, the ASP's electrical expenditure is in the range of 45–65% of the total plant energy cost (Reardon, 1995; Rosso and Stenstrom, 2005a; 2005d).

Since the 1970s, fine-pore diffusers have been known to save substantial energy over coarse bubble diffusers and mechanical aerators. Fine-pore diffusers began replacing coarse bubble diffusers in new treatment plant designs in the 1980s and have been retrofitted in previously constructed treatment plants. Retrofitting became a popular way of reducing plant energy requirements in the 1980s and continues today, where almost all municipal treatment plants have been retrofitted. Treatment plants operated by the City of Los Angeles and the County Sanitation Districts of Los Angeles County are examples of this process. The Glendale Plant was the first retrofitted plant with one tank equipped with Norton ceramic dome diffusers. The Whittier Narrows plant was next and was equipped with Sanitaire ceramic disc and Norton ceramic dome diffusers. The remaining active sludge plants were retrofit over the next decade. Substantial energy savings was obtained through these retrofits although the initial savings of 50% of the blower costs were not maintained. The problems associated with maintaining the high energy savings are diffuser fouling and scaling. It was not uncommon to experience a 25–50% decline in aeration efficiency over the first one or two years of service. The decline is reversible in many cases but requires diffuser cleaning, which can be time consuming and may disrupt routine treatment plant operations. Operators and managers were reluctant to invest in cleaning, especially if the need for cleaning and its benefits could not be easily measured.

At the same time that fine-pore diffusers were being introduced, a new oxygen transfer efficiency (OTE) measurement device was also developed, which measured the oxygen content of the gases evolving from the aeration tanks (off-gas) and did not require air flow measurements to affect a mass balance. The technique was mathematically eloquent and simple. However, it required an expensive analyzer and a trained technical team to measure and interpret the data, ranging in cost from $5,000 to $20,000 to perform a single evaluation and requiring one to three days. The lack of a real-time method for measuring OTE has impeded energy conservation and the installation of second and third-generation fine-pore diffusers.

1.1.1.   Methods for Increasing Energy-Efficiency in the ASP

At present, there are several methods for increasing energy-efficiency in the ASP, the most important being:

- Utilization of fine-bubble aerators

- Optimization of dissolved oxygen (DO) control systems

- Implementation of diffuser maintenance/cleaning schedules

Fine-Bubble Aerators

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Over the past 30 years, after the energy crisis of the 1970s, fine bubble (also referred to as fine-pore) aerators (also called diffusers) have experienced widespread application. Despite higher capital costs, increased energy costs make fine-bubble installations the most economically-viable solution in most cases. At present, fine-bubble aerators are the most commonly used aeration technology for municipal wastewater treatment in the United States and Europe.

There are three main commercially available aeration technologies: Surface mixing, coarse-bubble, and fine-bubble aeration. Surface mixing creates a gas-liquid interface by shearing the liquid surface with a turbine or mixer. Coarse-bubble aerators inject air from open or slotted pipes, venturi throttles, or sparger heads into the wastewater with resulting bubbles larger than 50mm. Fine-bubble aerators differ from the coarse-bubble aerators in that they release bubbles through the small pores of a sintered ceramic or the punched orifices of a polymeric membrane. The resulting bubbles have a typical diameter of (2–20mm), depending on diffuser type, airflow rate, and diffuser fouling/scaling conditions.

Fine-bubble diffusers exploit the following advantages of mass transfer associated with small bubbles:

- Larger mass-transfer interfacial area

- Smaller bubble rising velocities (i.e., larger mass transfer contact time)

- Lower specific energy required per wastewater unit volume

Furthermore, fine-bubble aeration devices have the additional advantages of lower stripping of volatile organics and lower heat loss.

Optimization of DO Control Systems

DO control systems are a well-known, widely diffused, and long-term application in WWTPs. These systems are based on a network of DO measuring probes. These probes are essentially fuel cells, with a semi-permeable membrane before the electrode. This membrane selectively allows the passage of oxygen molecules towards the electrode. The fuel cell burns the DO and returns a voltage signal. The signal is proportional to the concentration of oxygen in the water solution.

When properly cleaned and maintained, DO probes offer point readings of the DO concentration in the ASP. The DO control systems only measure the local values of DO concentrations. Thus, a major drawback of the DO control systems is their failure to quantify the OTE. Operators at WWTPs with DO control systems may use air line headloss and flowrate to estimate energy costs. Although, DO control systems measure an effect of mass transfer, they do not quantify the mass transfer itself. DO control systems do not provide information on the status of the diffusers or their operating efficiency, which is necessary to calculate energy requirements. The off-gas technique (see §3) is the only measurement that allows one to calculate the percentage of oxygen transferred to the wastewater, enabling the calculation of (not estimate) energy requirements.

Implementation of Diffuser Maintenance/Schedule.

Fine-bubble diffusers have the disadvantage of experiencing aging with time in operation (Rosso and Stenstrom, 2005b). Diffuser aging is due to the following:

- Inorganic scaling (precipitation of carbonates, sulfates, and silicates)
- Biological fouling (attachment, formation and decay products of a microbial biofilm)
- Composite of scaling and fouling

The most commonly occurring scenario is a composite fouling/scaling, with inorganic precipitated crystals embedded into a matrix of biological microbial polymers. As shown in Figures 1–3, fine-bubble diffusers typically show fouling/scaling visible to the naked eye after a long time in operation without cleaning.

Figure 1. Typical fouling/scaling effect on a fine-bubble aerator ASP before cleaning. (Rosso and Stenstrom)

Figure 2. Typical fouling/scaling effect on a fine-bubble aerator ASP after cleaning performed by tank-top hosing. (Rosso and Stenstrom)
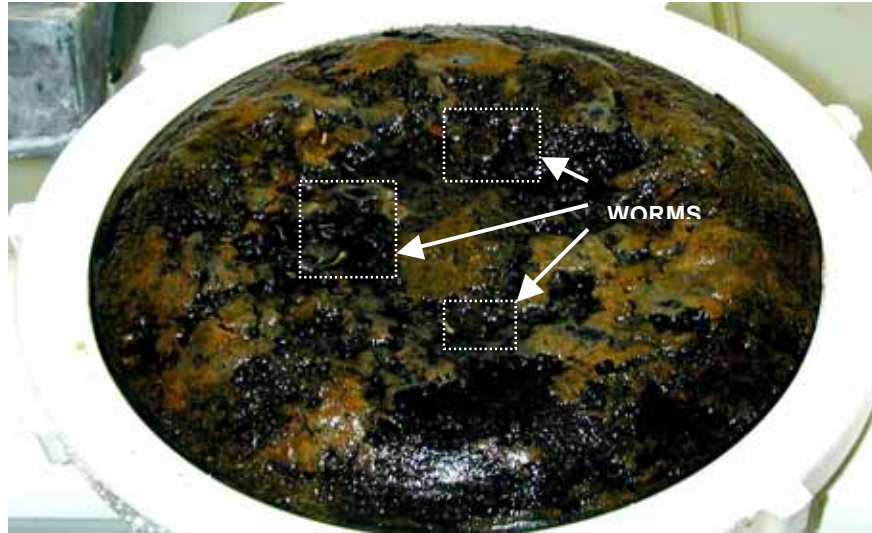
Figure 3. Membrane diffuser from a different plant three years after cleaning (Note: the superficial biological growths highlighted are worms). (Rosso and Stenstrom)

Figure 4 shows the decline of the aerator efficiency parameters with increasing time in operation. A recently published study found no evidence of different α (alpha factor) factors for different makes or models of fine-bubble diffusers, but found that the key parameters affecting OTE are the microbial mean cell retention time, airflow rate, diffuser depth, and the total bubbling area (Rosso et al., 2005). In existing fine-bubble installations (with a known plant geometry) for a given load, only the airflow rate can be manipulated to maximize OTE.
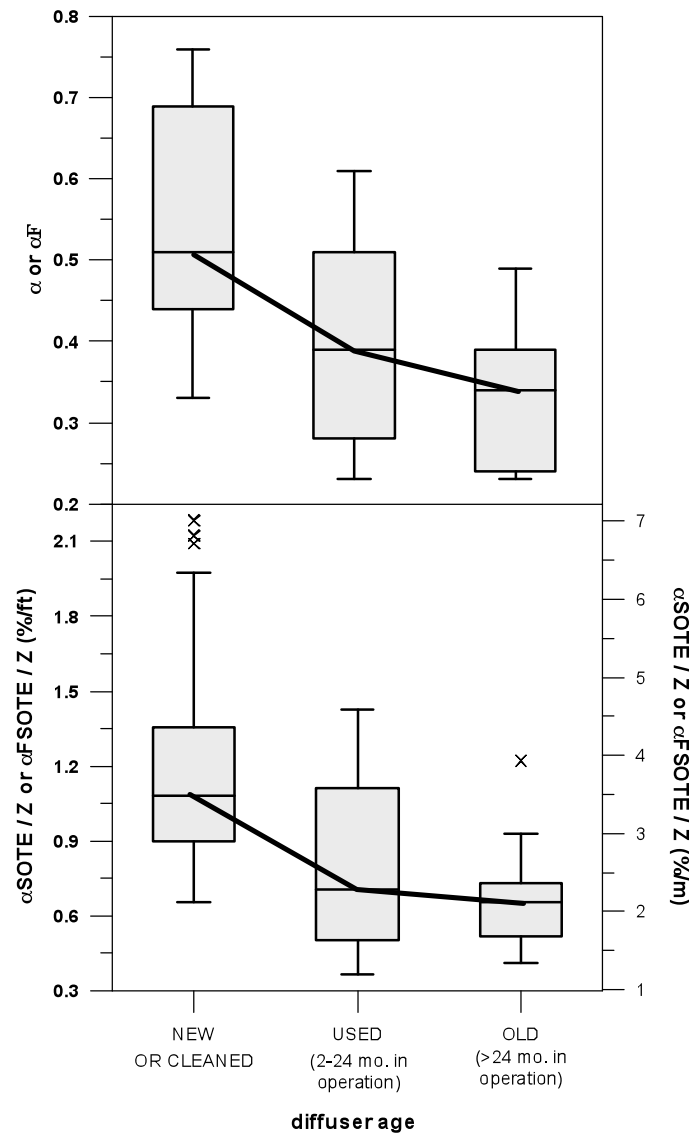
Figure 4. Efficiency decline for fine-bubble diffusers (after Rosso and Stenstrom, 2005b and 2005c). Aerators are grouped in new (within 1 month from installation or cleaning), used (within 24 months from installation/cleaning), and old (over 24 months). Standard OTE (SOTE)/Z is the specific field OTE per unit depth. And SOTE/Z are used for new aerators and old aerators.

To access OTE, the Standard Guidelines of American Society of Civil Engineers (1997) recommend three types of in-process water testing methods:

- Non-steady method, using pure oxygen or hydrogen peroxide, for surface or diffused aeration systems.
- Off-gas analysis for diffused aeration systems.
- Tracer racer method for both surface and diffused aeration systems.

The Standard Guidelines also describe, but do not recommend, two other methods based upon ex-situ oxygen uptake rate measurements and liquid-phase mass balances.

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Methods based upon ex-situ oxygen uptake rate measurements, usually called the steady-state method, and the use of a biological oxygen demand bottle for uptake measurement, create severe limitations on applicability because of the inability to produce conditions in a sample bottle that properly reflect the conditions in an aeration basin. The inability to measure an accurate oxygen uptake rate creates artificially low or high oxygen transfer estimates, which have sometimes been explained as a biologically enhanced transfer (Albertson and DiGregorio, 1975). A history of the errors and problems introduced by ex-situ measurements have been discussed in detail by Mueller and Stensel (1990), who concluded that there was no evidence for biologically enhanced oxygen transfer rates in the ASP. In-situ oxygen uptake measurements, such as those taken by process respirometers, have not been extensively used for in-process testing; there is little to no long-term experience in this use.

The major advance described by the Standard Guidelines is the off-gas analysis method that was developed by Redmon et al. (1983) under the sponsorship of the United States Environmental Protection Agency and American Society of Civil Engineers. This method uses an oxygen gas sensor to measure the oxygen mole fraction in the off-gas. By removing the carbon dioxide and water vapor from the off-gas, and assuming no change in nitrogen fraction, Redmon et al. (1983) showed that the OTE could be calculated directly from the mole fraction measurements and did not rely on volumetric gas flow rate. This technique improved on the methods used previously by a number of investigators, including Sawyer and Nichols (1939), Hover et. al. (1954), Pauling et al. (1968), Prit and Callow (1958), Downing (1960), Conway and Kumke (1966) and Leary et al. (1968).

The main reason preventing wide installation of off-gas monitoring in WWTPs is its complexity in operation. The classic instrument uses a vacuum cleaner to collect the off-gas stream from the aeration tank through a floating hood. The original manual off-gas setup, including the analyzer, the capture hood, and a vacuum pump, requires a crew of at least two to three expert investigators to operate, which considerably decreases the flexibility and applicability of this technique.

1.2. Project Objectives

The main objective of this project is to develop a portable, light-weight, and simple to operate OTE monitoring device to help operators assess their aeration efficiency. To achieve this objective it is necessary to:

- Investigate the economic saving of cleaning frequency for fine-pore diffusers.
- Build lab-scale and field prototypes of OTE measuring devices.
- Test extensively the prototypes in WWTPs.
- Build small-scale capture hoods.
- Develop a field testing protocol for operators..
- Create aerators' cleaning/maintenance schedules and protocols.
- Utilize the OTE measurements for a process economic analysis.

1.3. Report Organization

This report is a summary report of many tasks. Each task has its own report which can be found in the appendices. The task reports include: The Project Advisory Committee's (PAC) meeting

minutes, Technology Assessment Report, Blower Assessment Report, Market Assessment Report, and information on Technology Transfer. Readers can find an overview and brief descriptions of each task in the main body of this report. Detailed discussions on each task reports are included as independent reports in the appendices.

2.0 Project Approach

In accordance with our proposal, seven distinct tasks were identified as important elements to be studied. The list of these tasks is as follows:

- Task 1 – Project Administration
- Task 2 – Independent Assessment of the OTE Technology and Potential Benefits
- Task 3 – Development of a Fully Automated and Digitized OTE Equipment
- Task 4 – Development of OTE Testing Protocol
- Task 5 – Optimization of Blowers for Wastewater Aeration
- Task 6 – Assessment of Potential Market Applications
- Task 7 – Technology Transfer Activities

A summary description and discussions of these tasks are presented below:

2.1. Project Administration

The Project Administration task involved a number of sub-tasks as shown below:

- Coordination of the lines of communication between sub-contractors and the Energy Commission.
- Technical management of project activities .
- Administrative management of project reporting such as quarterly, annual, and meeting reports.
- Formation of the PAC.
- Organization and conduction of PAC meetings .

A PAC was formed to oversee the research work and provide feedback on the results. The PAC members were selected to review and recommend on:

- Field testing and protocol development.
- Plant operations improvement (i.e., operators training, cleaning frequency and methods, process upgrade, etc.).

The PAC was formed with the following wastewater experts:

- Dave Reardon   HDR Engineering Inc., energy audits specialist
- Henry Melcer   Brown & Caldwell, process designer
- Rod Reardon   Camp, Dresser, and McKee Inc., process designer
- Mike Selna   Sanitation Districts of L.A. Co., WWTP operations mgr.
- Keith Carns   EPRI Solutions Inc., energy specialist
- H. David Stensel   Univ. of Washington, Professor - Biological Processes
- Omar R. Moghaddam City of L. A., Bureau of Sanitation, manager
- J.B. Neethling   HDR Engineering Inc., WWT technology director
- Shahid Chaudhry   California Energy Commission, *Ex Officio*
- Paul Roggensack   California Energy Commission, *Ex Officio*
- Lory Larson   Southern California Edison, *Ex Officio*
- Roger Sung   Utility Technology Associates, *Ex Officio*

In addition to providing valuable feedback and input to the project, the PAC committee held three PAC meetings during the course of this project. These meetings proved extremely valuable to the project team both in conveying operational concerns as well as application requirements. A detailed discussion of the PAC Meeting Minutes is included in Appendix I.

2.2. OTE Technology Independent Assessment

The objective of this task was to provide an independent and unbiased critique of the practicality and usefulness of the OTE technology to the wastewater industry. The technology assessment report covered the following subject areas:

- Wastewater aeration and energy usage overview
- Problems associated with aeration
- Study objectives
- Aeration technology overview
- Monitoring technologies available for aeration control
- Critical review of the OTE technology
- Potential benefits
- Conclusions/recommendations

The following were the most significant findings:

- Although several technologies are available for aeration monitoring, the off-gas technology is the method of choice for diffused aeration systems involving either plug flow or complete mixed reactors.
- Off-gas technology is the only technique available that measures the actual oxygen transferred to the wastewater.
- Other technologies identified in this task may measure an effect of mass transfer, such as DO, but not the mass transfer directly.
- The evaluation study further recommends that the UCLA's research team be encouraged to accelerate its development of a portable, digitized, automated, and simple to operate OTE system.
- Significant energy savings can be realized with the commercial deployment of this product.

A detailed discussion of this report can be found in the appendices under Appendix II.

2.3. OTE Technology Equipment Development

Motoring protocols were first assembled and tested in the laboratory under a controlled environment where lab-scale devices are more sensitive and accurate in providing reference values to test the apparatus. Based upon the equipment used and its performance in the lab-scale tests, bread-board versions of the field-scale analyzers were built. These prototypes were tested in selected full-scale WWTPs in Northern and Southern California.

2.3.1. Lab-Scale Protocol and Experiment

The lab-scale oxygen apparatus (shown in Figure 5) used in the lab-scale experiment is a full-featured unit with precise and accurate measurements for a wide range of measuring scales, thus allowing fine-tuning, debugging, and sensitivity analysis. The laboratory analyzer, because

of its sophistication, is rather costly. The portable, lightweight, and low cost fuel cell prototype unit to be used in the field will be tested against this apparatus.

The lab-scale protocol and experiment was set up as shown in Figure 6. A column 5 feet (ft) deep and 7 inches (in.) in diameter was used as a batch reactor. For this reactor, a fine-pore membrane, collected from a full-scale system, was used as the air diffuser. A DO probe was placed in the water and a capture hood was used to cover the top of the column. The hood collected and conveyed the off-gas stream to an oxygen cell analyzer. Analog voltage signals were produced by both the DO meter and the oxygen cell, and were captured and recorded by a data logger.

The experimental procedure basically follows the standard of the clean water test published by the American Society of Civil Engineers in 2006. For this test method, sodium sulfite is used to scavenge DO according to the reaction in Equation 1. Equation 1 is shown below:

$$Na_2SO_3 + \frac{1}{2}O_2 \xrightarrow{\;CoCl_2\;} Na_2SO_4$$
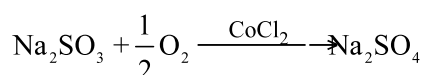
Following the oxygen removal by oxidation of sodium sulfite that occurs almost instantaneously, the aeration device provides air to the batch system and oxygen continues to be consumed according to the stoichiometry in Equation 1. The system experiences re-aeration when the excess sodium sulfite is completely converted into sulfate. By analyzing the slope of the DO re-aeration curve or the oxygen fraction in the off-gas, the oxygen transfer coefficient k_La can be calculated.

Figure 5. Lab-scale off-gas testing apparatus (Teledyne 9070 O2/CO2 analyzer) used in the laboratory (Rosso and Stenstrom)
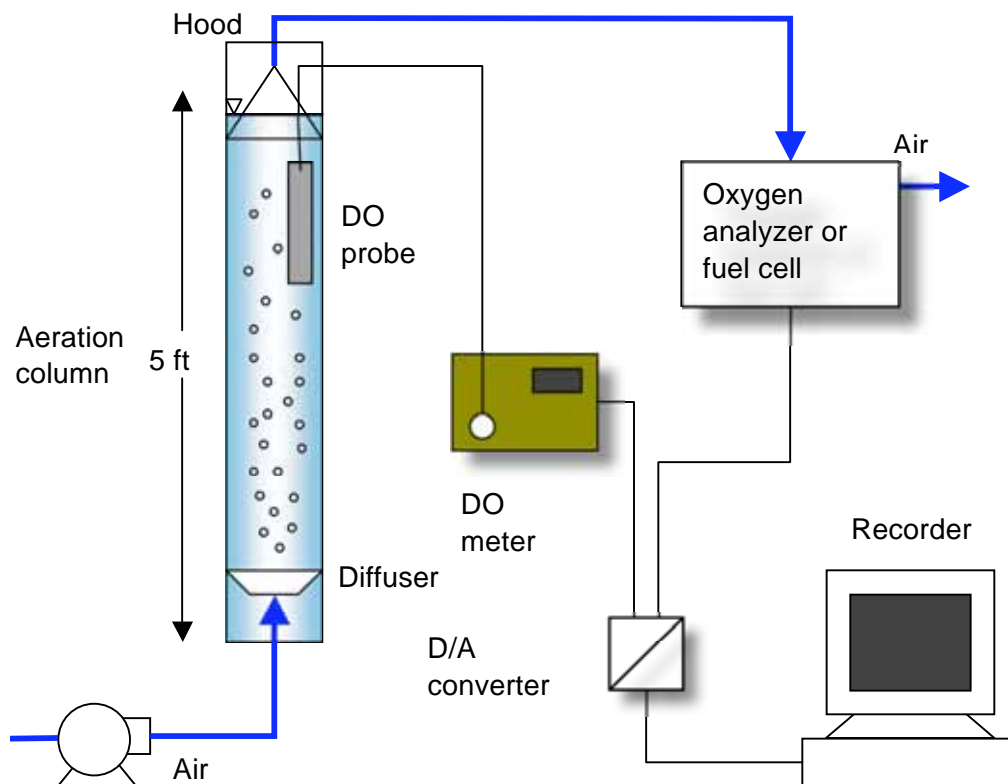
Figure 6. Schematic of a lab-scale off-gas testing apparatus

2.4. Field Technology Design and Testing

2.4.1. Design and Assembly of Field Prototype

Several units of field prototypes were assembled for plant testing and subsequent distribution. The field unit was designed and packaged for plant installation, i.e. it was smaller (about the size of a shoebox), of simple design, user-friendly, and low-cost (~$2,000). This apparatus was able to measure data in a narrower range than the lab-scale analyzer. The goal of the lab-scale system was to find and center the measuring range for the DO values to be used by the field unit within the ASP.

Figure 7 shows the schematic of the field automatic off-gas analyzer unit. This design incorporates the highest simplification of the off-gas monitoring device and maintains the measuring accuracy of the original device (Redmon et. al., 1986). A three-way valve controlled by a time-delay relay switches the connection in time-sequence from either the off-gas or the reference air into an O_2 fuel cell, in which the air flow is driven by the off-gas itself and a lab-scale vacuum pump (300 milliliter [ml]/minute, or 2 in mercury [Hg]). The O_2 fuel cell returns a voltage proportional to the O_2 partial pressure in the gas stream. For each measuring event, reference air and the off-gas are compared and the instrument is simultaneously calibrated after each measurement. The off-gas flow rate is calculated by measuring the air velocity in the air hose and recording each measurement to allow a flow-weighted average of the entire aeration

tank. Our full-scale testing modules produced an aeration efficiency database, which complements our previous extensive off-gas measurements (Rosso et al, 2005).
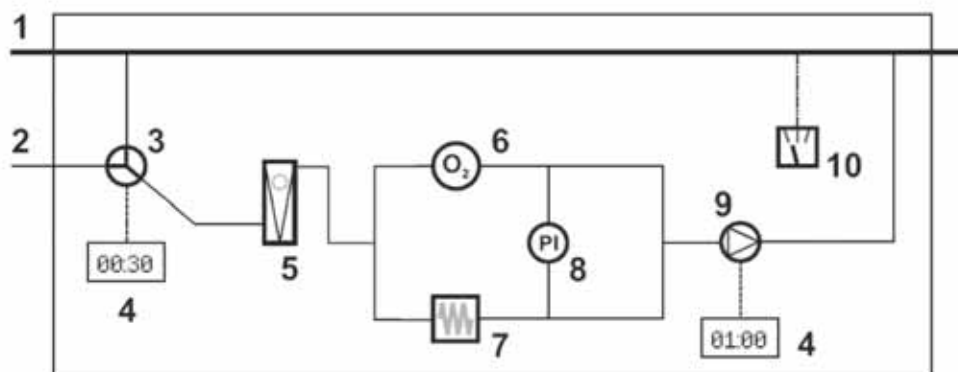
Figure 7. Schematic of the real-time automated off-gas analyzer. Key: 1) off-gas hose (from collection hood); 2) reference air intake; 3) 3-way valve; 4) time delay relay; 5) flow meter; 6) oxygen fuel cell; 7) resistance; 8) differential manometer; 9) vacuum pump; 10) air velocity meter. Solid lines are hydraulic lines, dashed lines are electrical connection.

2.4.2. Field Experiments – 24-Hour Tests

Field experiments were performed at a full-scale WWTP to illustrate the capability of real-time off-gas monitoring and to test our field prototype. The volumetric flowrate of this plant is approximately 10 million gallons per day (MGD). Figure 8 shows the schematic diagram of this plant and the testing hood positions. The plant contains four process tanks (19 ft in depth), each with four small anoxic sections and two aerobic sections. Before secondary treatment, an extra basin was provided to equalize the flow of primary effluent. In addition, the Modified Ludzack-Ettinger (MLE) pumps are equipped at the end of process tanks to recycle the process water. Following the process tanks are two aerated polishing tanks (15 ft deep). The aerobic zones of process tanks and polishing tanks are both equipped with a fine-pore, strip type diffuser system.

Two 24-hour tests were performed using both the original (manual) and our bread-board field-scale prototype unit. The first test was performed on the aeration tank five months after the diffusers were installed and the second test was performed immediately after a cleaning process of the diffusers eight months later. Both results were compared to a reference test performed. The positions of the off-gas hood were in the middle of the two aerobic sections and the first section of the polishing tank. The experiments measured the OTE, air flow, and off-gas temperature. Primary effluent samples were collected hourly to calculate the pollutant load as rate of oxygen demand. The power requirement and the potential costs/benefits were calculated by the integrated total oxygen transferred, where the main assumptions are $0.15/kilowatthours (kWh) of power cost and the annual interest rate of 4%.
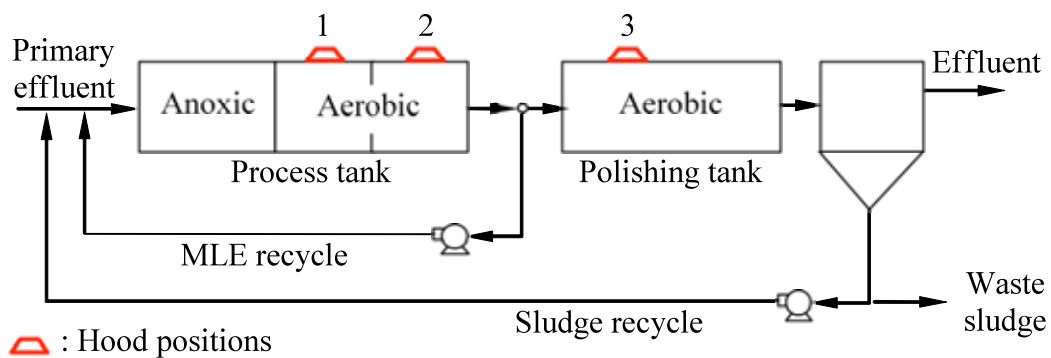
Figure 8. Schematic Diagram of the Nitrifying-Denitrifying Treatment Plant (headworks, primary clarifier, equalization basin and disinfection facilities not shown)

2.4.3. Applications in California

The off-gas field testing apparatus was evaluated at selected WWTPs. Table 1 summarizes the list of locations planned for testing. Small (2'x2') capture hoods were built and placed in-situ for data gathering. To further simplify the off-gas monitoring design, the future field-scale analyzer can be housed in a portable case with wheels, much like carry-on luggage for planes, or can be mounted onto the top of the hood as one single compact testing unit.

Plant	Location	Process Layout	Aeration equipment
Proposed First Choice WWTPs			
LA Glendale	City of Los Angeles, Bureau of Sanitation, Glendale, CA	Conventional, NDN*	9" membrane and ceramic discs
Whittier Narrows	Los Angeles County Sanitation Districts, Whittier, CA	NDN	9" membrane and ceramic discs
Central Contra Costa	Central Sanitary District, Martinez, CA	Plug Flow Conventional	14" ceramic discs
SOCWA Regional Plant	Laguna Niguel, CA	NDN	Parkson panels
Simi Valley	City of Simi Valley, CA	NDN	Aerostrip panels
Alternate WWTPs			
Tillman	City of Los Angeles, Van Nuys, CA	Conventional, NDN	Ceramic Domes and Discs
San Jose Creek	Los Angeles County Sanitation Districts, Whittier, CA	NDN	9" membrane and ceramic discs
West County	Richmond, CA	Nitrifying only	7" Norton Domes

* NDN – nitrification and denitrification

Table 1. Testing locations

2.5. Blowers Assessment

Blowers are low-pressure compressors used for subsurface aeration. Blowers are classified as either positive displacement (PD) or centrifugal. PD blowers are generally constant flow, variable pressure flow devices while centrifugal blowers are generally constant pressure, variable flow devices. For all practical purposes, smaller plants use PD blowers or centrifugals and all larger plants use centrifugal blowers, with the largest plants most often using single-stage blowers.

Before the advent of efficient variable frequency drives (VFDs), there was little opportunity to modulate the flow of a PD blower without using expensive, low-efficiency variable ratio gearboxes. Some energy could be consumed by throttling the suction, or in other cases, excessive discharge flow could be vented at reduced pressure. Neither situation was very satisfactory. With VFDs, the flow is proportional to blower RPM (less a small fraction due to slippage), and a wide range of turn up or turn down is possible. By applying a VFD to an electric motor, the motor can be run at a higher or lower speed than its nominal rating, and can be started and stopped with less overheating. When traditional motors are started, about 300%

of the rated current is initially drawn to bring the motor to speed. This overheats the motor and in certain cases may reduce the ability for the motor to be started more than once in an extended period of time (e.g., not more than once per hour or work shift). At the same time, the increased initial current burdens the blower energy cost, especially if drawn during peak power rate periods. Diurnal cycles in wastewater treatment typically result in highest treatment requirements during the daytime, when power has higher cost. Therefore, reducing the power drawn of motors during normal operation as well as for motor startup is very important.

Current control techniques for aeration systems are typically based on feedback signals provided by DO probes immersed in the aeration tanks. To optimize the energy consumption of aeration systems, the best blower control strategy is to supply the minimum amount of process air to the wastewater treatment, while meeting substrate removal and DO requirements.

When evaluating blower upgrades, several factors should be taken into consideration. Blower units must be chosen, accounting for redundancy, to allow scheduling shifts and operation and maintenance requirements. In order to avoid sudden increases in air flow rates (AFRs), and therefore of energy demand, blowers with tuning capability are always recommended (i.e., PD blowers with VFDs or centrifugal blowers equipped guide vanes and/or VFDs, etc.). These blower systems allow the variation in AFR within their operating range, which accommodates the variations of load in the treatment plant. When the variation exceeds the blowers' operating range, one more blower is activated, as in traditional systems. The benefit of tuning systems is a smoother transition within the range of AFRs, which is reflected in increased ease of management in terms of energy costs. The complete blower report is in Appendix III.

2.6. Assessment of Potential Market Application

Market assessment is an integral part of any new technology rollout program. Information developed through market assessment provides market intelligence on customers' interest to adopt the new technology. The original intent of this study was to have Southern California Edison (SCE) energy service representatives conduct the market survey internally. This plan was changed when it was discovered that BacGen, a very reputable wastewater consultant, was under contract at the time to SCE on a different technology deployment program for the same wastewater industry planned for survey. By having BacGen conduct the survey/assessment concurrent with their on-going activities, the time required for the survey, as well as cost for training of SCE personnel prior to the survey, was reduced. Consequently, the survey was performed more cost-effectively, without utility bias, and by skilled professionals in this field.

Study results showed that the majority of the WWTP operators have little interest in the off-gas technology. The most common reasons given by operators were:

- Lack of time.
- No interest to learn.
- Lack of understanding/too complex to be useful.

Off-gas testing consultants and diffuser suppliers also shared similar negative comments. A detailed discussion of the industry market survey is included in Appendix IV.

2.7. Technology Transfer Activities

Technology transfer is the last stage in the study's effort to make the knowledge gained, and experimental results and lessons learned, available to key decision-makers and the wastewater industry in general. Key elements in the technology transfer plan include:

- Conduct two workshops in technical forums to the wastewater industry, regulatory agencies, municipalities, electric utilities, and the general public in two locations, one in Northern California and one in Southern California.

- Publish and present papers at water and wastewater symposiums. Examples of these include the following:
  - 25th West Coast Emergency Management Congress Conference
  - IWA (International Water Association) Leading-Edge Conference on Water and Wastewater Technologies
  - IWA 4th Specialist Conference on Efficient Use and Management of Urban Water Supply
  - Publish Summary Report of OTE Study to Wastewater Industry and Member Electric Utilities

Workshop presentation material and list of attendees for each workshop are presented in Appendix V. The technical papers for the conferences above are presented in Appendix VI.

3.0 Project Outcomes

The results of the off-gas lab experiments and field tests are presented in §3.1 and §3.2, respectively. The lab experiments included a membrane cleaning study and the test results from the lab-scale protocol. The membrane test showed and quantified the effects of diffuser performance, and hence the importance of diffuser cleaning. Field experiments were conducted at selected full-scale WWTPs. The results of these 24-hour field tests were compared with our long-term observation (Rosso et al., 2005, 2006a, 2006b), which provided useful information to the development of our real-time monitoring system.

In addition, economic analysis of aeration costs was performed as a case study based upon our field experiments at a selected treatment plant. To clearly demonstrate the potential benefits of diffuser cleaning, energy savings were calculated and presented in total power and dollars. The design layout and field-scale prototypes built are presented in §3.3 and §3.4. In §3.5, hood size analysis was performed. The hood dimensions are important when performing off-gas analysis. The area under the hood must be representative of the entire area of the tank. In §3.6, several case studies from full-scale WWTPs in California were presented. The potential energy savings that might be provided by the monitoring technique were presented in actual numbers, such as unit wastewater treated and capital cost for California. The last sub-section, §3.7 of this report, addresses air blowers and air distribution systems to provide a complete picture which shows an equally important parameter to consider in energy savings, i.e. blower performance.

3.1. Lab Experiments

3.1.1. Membrane Cleaning Experiment

In order to compare the performance of fouled and cleaned diffusers, several experiments are provided. Figure 9 shows a half-cleaned diffuser. This diffuser image was collected from a local treatment plant operating at low mean cell residence time (MCRT). Before cleaning, the membrane was covered by a layer of biomass and living worms (left side). Half of this diffuser was then cleaned by manual scraping and tap water rinsing. The result can be easily observed: totally different sizes of bubbles are produced from the same diffuser. Before cleaning, bubble diameters are about 4mm, after cleaning, the diameters are reduced to 1–2 mm. Smaller bubbles provide a larger specific surface area and therefore higher transfer efficiency.

Figure 9. Photograph of a half-cleaned diffuser: before cleaned (left part of the diffuser) the diffuser was covered by a layer of biomass and the bubbles produced are big; after cleaned (right) the bubbles turn to smaller, similar to a new diffuser. (Rosso and Stenstrom)

Clean water tests and dynamic wet pressure (DWP) tests were applied to confirm the improved performance of cleaned diffusers. The same diffusers were tested before and after cleaning with tap water and acid. Figure 10 shows the results of this test. After cleaning, the gas transfer coefficient recovered significantly; acid cleaned diffusers recover their efficiency values and approach new diffusers' performance. DWP tests also show similar results for head loss variations; uncleaned diffusers show a dramatic increase in head loss, while cleaned diffusers maintain a more moderate increase (Figure 11). However, no significant difference was found between the cleaning methods. Acid cleaning may not be effective for opening bio-fouled pores but may be effective for removing inorganic scales formed on the pores before complete fouling.
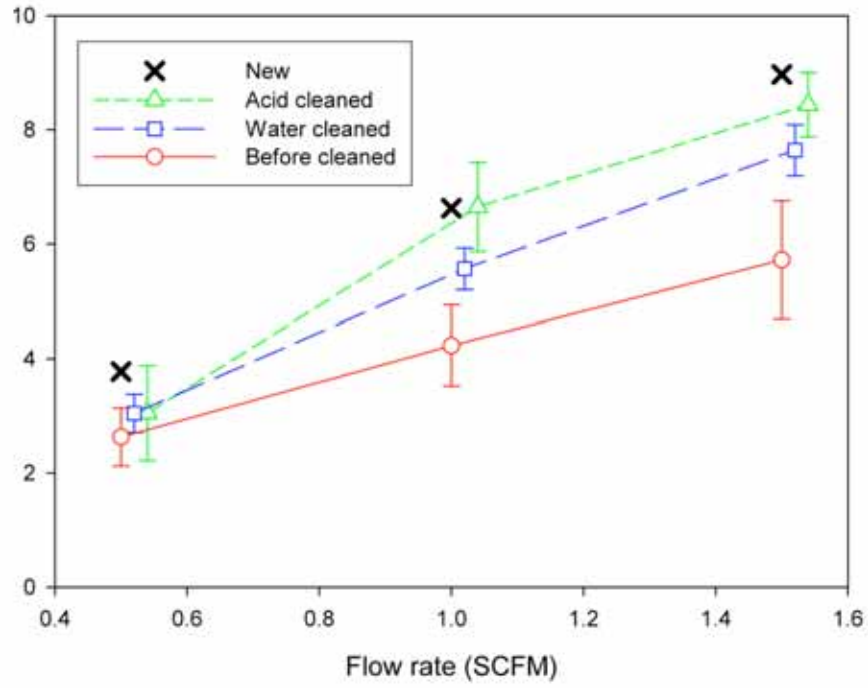
Figure 10. Comparison of OTE of uncleaned, water cleaned, and acid cleaned diffusers.
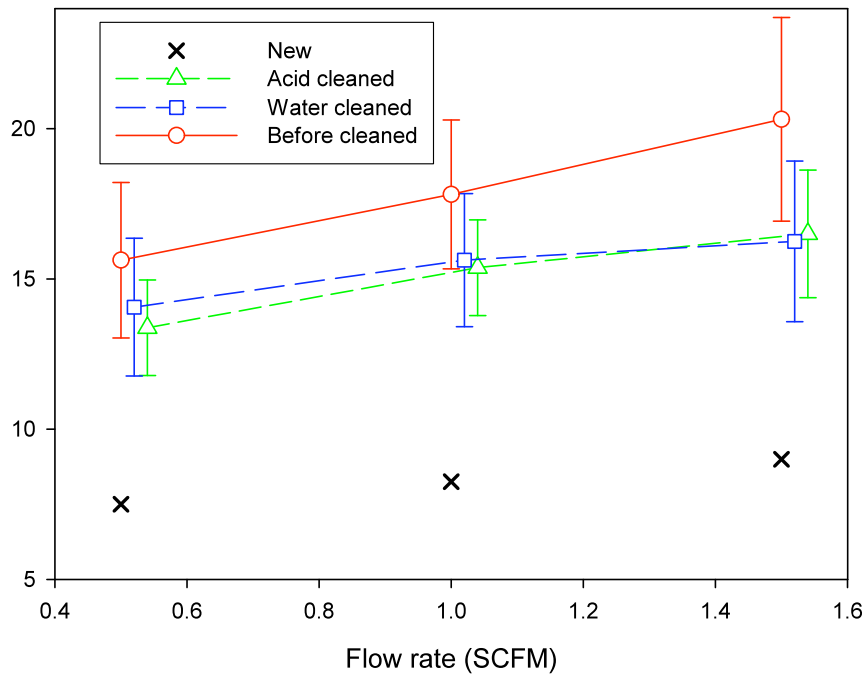
Figure 11. Comparison of headloss for uncleaned, water cleaned, and acid cleaned diffusers.

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3.1.2. Clean Water Test With Off-Gas Apparatus

Lab-scale testing was set up as shown in the apparatus displayed in Figure 12. A column 5 ft deep, with a 7-in diameter, was used as a batch reactor and a fine-pore bubble stone was used as an air diffuser. A DO probe with stirrer was placed in the water, and a capture hood covered the top of the column. The hood collects and conveys the off-gas stream to an oxygen cell analyzer. Analog voltage signals produced by both the DO meter and the oxygen cell were recorded by a data logger.
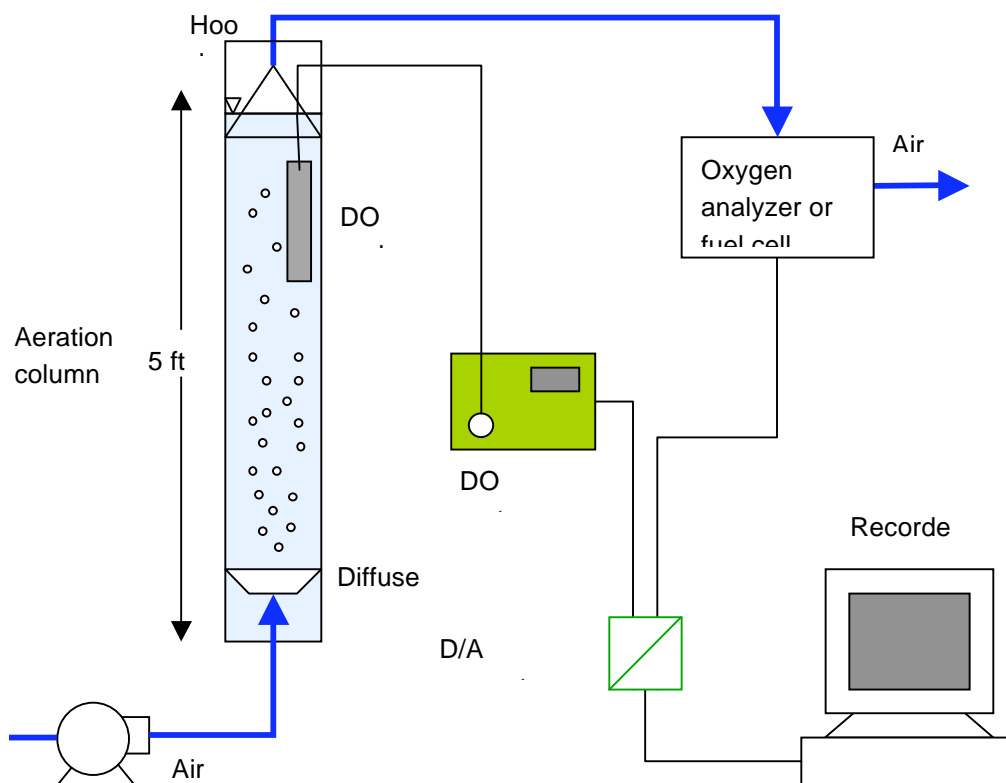
Figure 12. Lab-scale off-gas testing apparatus

In this experiment, sodium sulfite is used to scavenge DO according to the reaction. See Equation 2 below:

$$Na_2SO_3 + \frac{1}{2}O_2 \xrightarrow{\text{CoCl}_2} Na_2SO_4$$
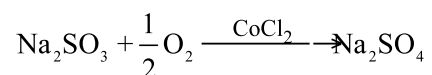
Following the oxygen removal by oxidation of sodium sulfite occurring almost instantaneously, the aeration device provides air to the batch system and oxygen continues to be consumed according to the stoichiometry in Equation 2, and when the excess sodium sulfite is completely converted into sulfate, the system experiences re-aeration. By analyzing the slope of the DO re-aeration curve or the oxygen fraction in the off-gas, the oxygen transfer coefficient k_La can be calculated.

The dynamic status of the DO and the off-gas oxygen fraction is shown in Figure 13. The same patterns of DO and off-gas oxygen fraction can be observed, showing that the oxygen in the water is first segregated and then dissolved. In Fig.13, the first rapid decline of DO concentration corresponds to the addition of sodium sulfite and cobalt chloride. After a steady-state plateau, where the excess sulfite is converted to sulfate (Equation 2), the DO concentration increases (re-aeration process).

Tank depth shows the most significant effect in our sensitivity analyses. Using a 5-ftdeep reactor, during the steady-state oxygen scavenging (pink plateau in the graph), the oxygen fraction in the off-gas is 18.07% (green plateau in the graph). The difference between this value and the O_2 ambient concentration (20.99%) is large enough to be accurately recorded. Previous experiences using a 2 ft deep tank showed a difference in O_2 concentration between the off-gas and the ambient too small to be quantified. In a 2 ft tank, bubbles require less than 1 second to transport from diffuser to water surface. The short retention time makes the difference of off-gas and ambient not measurable. This difference becomes obvious when water depth is greater than 5 ft. Since the depth of aeration tanks are much larger than 5 ft, the difference of oxygen concentration in influent air and off-gas is definitely measurable and serves as a good index of oxygen transfer.
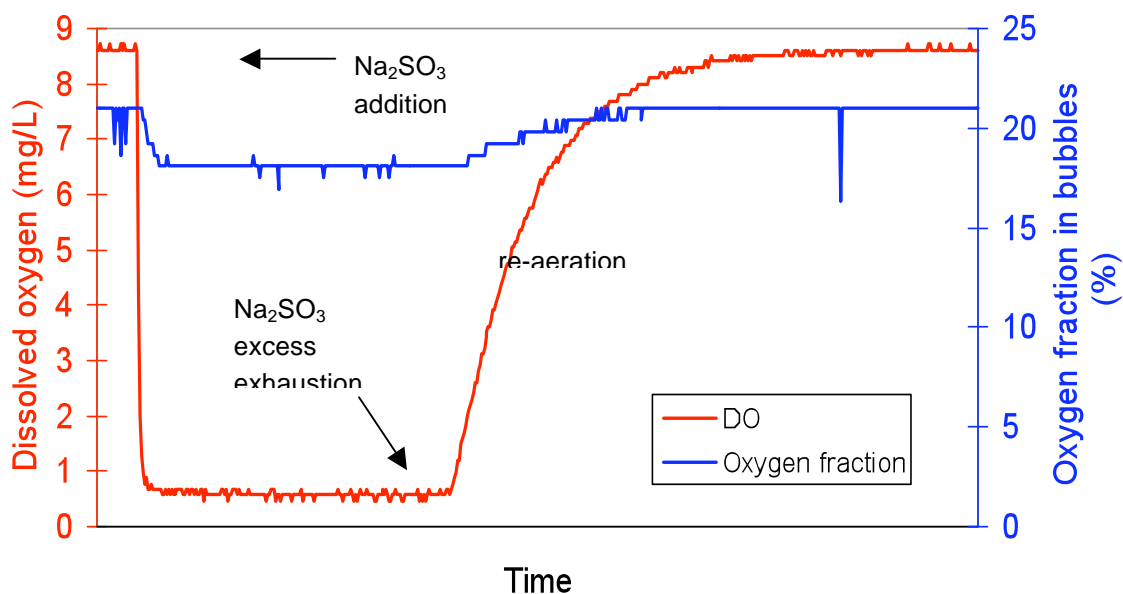
Figure 13. Dynamic status of DO and oxygen fraction in off-gas of a clean water test

3.2. Field Experiments

Field experiments were performed in a full-scale WWTP to illustrate and validate the calculation. The capacity of this plant is approximately 37,800 m³/day (10MGD). Figure 14 shows the schematic diagram of this plant and the testing hood positions. The plant contains four process tanks (5.8 meters (m), or 19 ft in depth), each with four small anoxic sections and two aerobic sections. Before secondary treatment, an extra basin equalizes the flow of primary effluent, and the MLE pumps used to recycle the process water are equipped in the end of process tanks. Following the process tank are two aerated polishing tanks (4.5m, or 15ft deep). The aerobic zones of process tanks and polishing tanks are equipped with a fine-pore strip type diffuser.

Two 24-hour tests have been performed using both the original (manual) and our bread-board field-scale prototype. The first test was performed five months after the diffusers installation and the second test was performed immediately after a cleaning process of diffusers eight months later. Both results are compared with a reference test performed one month after the diffuser installation. The off-gas hood positions are in the middle position of the two aerobic sections and the first section of the polishing tank. The experiments measured the OTE, air flow, and off-gas temperature; and primary effluent samples were collected hourly to calculate the pollutant load as a rate of oxygen demand. The power requirement and the potential costs/benefits are calculated by the integrated total oxygen transferred with conversion factors in United States basis, where the main assumptions are 0.15 United States Dollars (USD)/kWh of power cost and an annual interest rate of 4%.
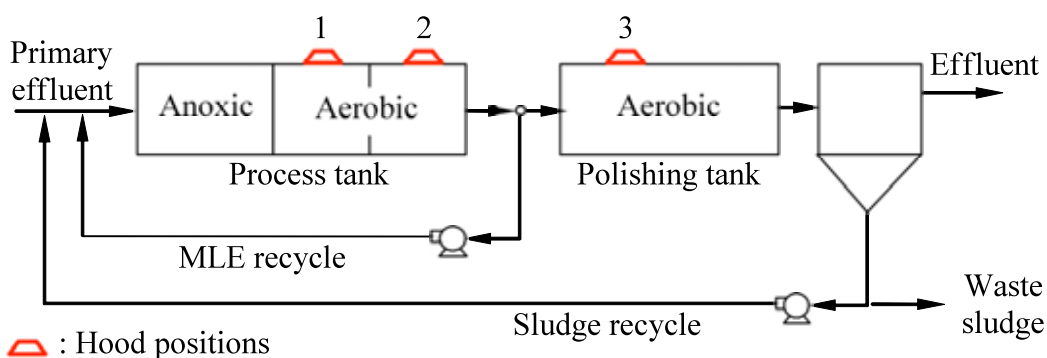
Figure 14. Schematic Diagram of the Nitrifying-Denitrifying Treatment Plant (headworks, primary clarifier, equalization basin and disinfection facilities not shown)

3.2.1. Results of 24-Hour Tests

Figure 15(a) shows the behavior of OTE compared to the AFR over a 24-hour cycle; when the AFR is at its maximum, OTE is at its minimum, and vice versa. The AFR is highest when the oxygen demand (i.e., the carbonaceous chemical oxygen demand (C-COD) is highest, which is reflected in low OTE and low alpha values. In addition, alpha-factors calculated from αSOTE (measured with the off-gas technique) and manufacturer's clean water data (SOTE) are shown in Figure 15(b). Although diurnal cycles of OTE measurements were reported previously (Libra et al., 2002), this is the first report of a time-series for alpha factors. The patterns of alpha and C-

COD have analogous behavior as OTE vs. AFR. This result shows that the off-gas reading (OTE) carries valuable information on AFR and load. For a given load, the off-gas signal can be used as a feedback control to regulate AFR to its minimum possible value, while achieving the same level of treatment and predicting the influent load concentration.
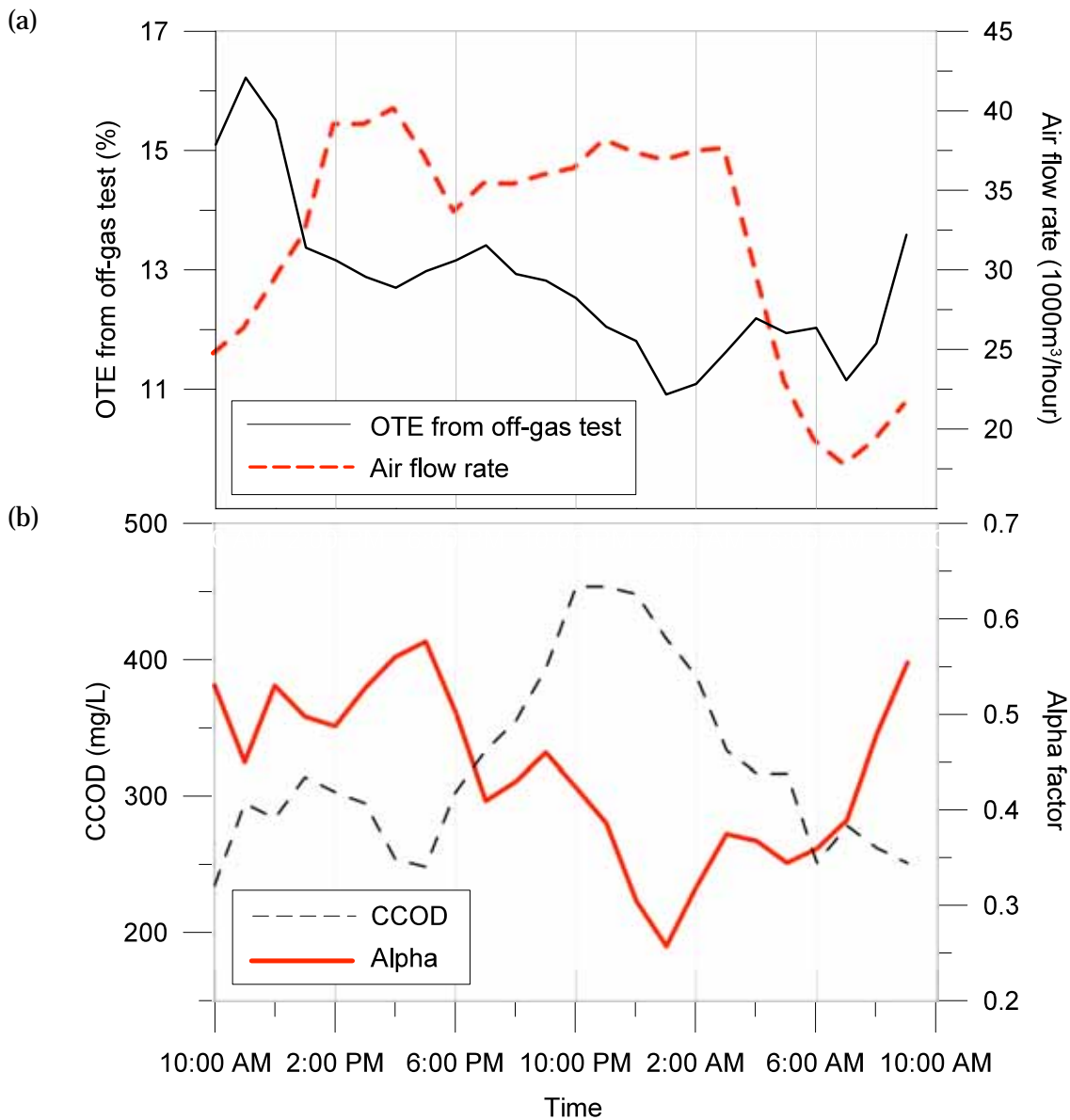
Figure 15. (a) OTE and AFR calculated from off-gas testing during a 24-hr. (b) C-COD and alpha-factor estimated from off-gas analysis, during the same period.

3.2.2. Comparison of 24-Hour Test Results to Long-Term Observation

Figure 16 shows the correlation between the alpha factor and air flux (AFR per unit of diffuser area, $m^3 \cdot s^{-1} \cdot m^{-2}$). The results were calculated from three different experiments made up of one clean water test and two process-water off-gas tests. In both off-gas tests, the results of a short term 24-hour measurements of αSOTE are negatively correlated with the air fluxes, which confirmed our previous long-term studies (Rosso et al., 2005). In addition, αSOTE is approximately half of the clean water SOTE (labels on the graph). The process water αSOTE has different patterns for different time in operation. Diffusers that have been in operation for a longer period without cleaning are fouled, which is shown by a more rapid decline in performance with increasing air flux (labeled "before cleaning" in Figure 16).
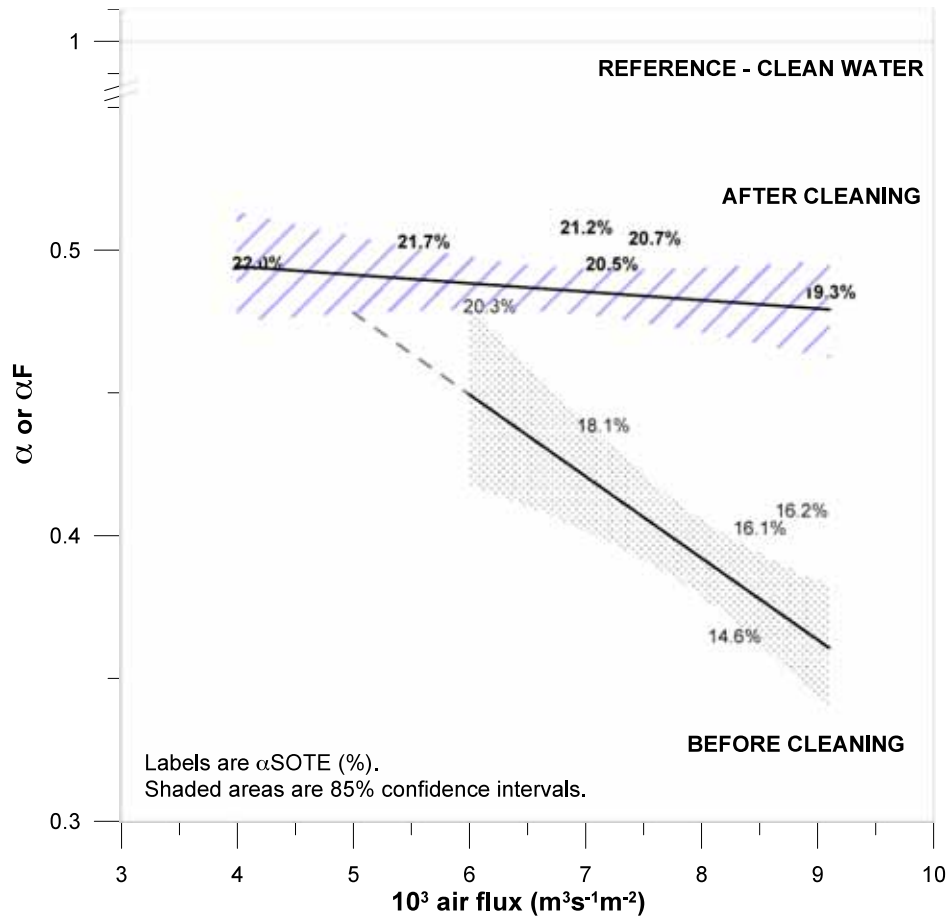
Figure 16. Correlation between SOTE and diffuser air flux (curve zones represents 95% confidence, Leu et al., 2007)

3.2.3. Energy Expenditure Due to Diffuser Fouling

Table 2 shows the aeration tank characteristics, the oxygen transfer data gathered from off-gas tests, and the energy consumptions calculated with our plant-cost algorithm (Rosso and Stenstrom, 2006a). The results suggest that the cleaning procedure improves OTE from 16.1% to 18.6%, thus reducing energy requirements from 235kW to 193kW, or 850 USD/day to 695 USD/day. Since the first test was performed eight months before cleaning and the diffuser fouling could be more serious during this period, the actual total saving must be greater than the number calculated.

Table 2. Results of off-gas tests and energy cost estimation

| Tests	Results or properties	Process Tank (×4)		Polishing Tank (×2)	Total
		Section 1	Section 2		
Background	Section dimension (m^2)	17.3 × 28.8	17.3 ×28.8	85.3×11.4	1969
	Depth (m)	5.8	5.8	4.5	-
	Number diffusers	71(×4)	56(×4)	127(×2)	762
Test 0 (Reference)	AFR (m^3s^{-1})	1.49	0.87	0.38	2.74
	aSOTE (%)	17.5	18.3	18.9	-
	Power/oxygen transfer rate (OTR) (kWh/KgO_2)	0.13	0.10	0.29	0.13
Test 1 (Before cleaning)	AFR (m^3s^{-1})	1.34	1.01	1.00	3.35
	aSOTE (%)	15.8	16.3	13.4	-
	Power/OTR (kWh/KgO_2)	0.14	0.13	0.34	0.17
Test 2 (After cleaning)	AFR (m^3s^{-1})	1.16	0.89	0.70	2.75
	aSOTE (%)	18.6	18.5	10.82	-
	Power/OTR (kWh/KgO_2)	0.13	0.12	0.44	0.15

The results of the 24-hour tests confirm, along with the authors long-term observation, that the alpha factor is affected by load of contaminants, and OTE is negatively correlated with AFR (Rosso et al., 2005); detailed discussion has been shown in Leu et al., 2007). This paper further calculated the power costs in USD of the experiment in WWTPs. Based upon our former studies (Rosso et. al., 2005, 2006), it is suggested that the fine-pore diffusers should be cleaned at least once every two years. Since diffuser fouling is a long-term process and describes the increase of power consumption on a monthly basis; the results of the hourly measurement were integrated to calculate the daily oxygen supplied and transferred.

Figure 17 shows the total power consumption, the costs due to diffuser fouling, and the benefits gained by diffuser cleaning. The solid line represents the total power consumption, which is equal to the basic power requirement (initial value, approximately 200kW in the figure) plus the power wasted due to diffuser fouling, and the dash line is the predicted value based upon the current observations. The red bars represent the normalized costs of power wasted (e.g. USD per mass of oxygen transferred). The potential saving of diffuser cleaning can be calculated by accumulating the costs times the interest rates (gray bars). Therefore, if one compares the

benefit of cleaning to the cleaning costs (e.g. tank drainage, diffuser replacement, and cleaning labor costs), an optimized time for diffuser cleaning would be predictable.
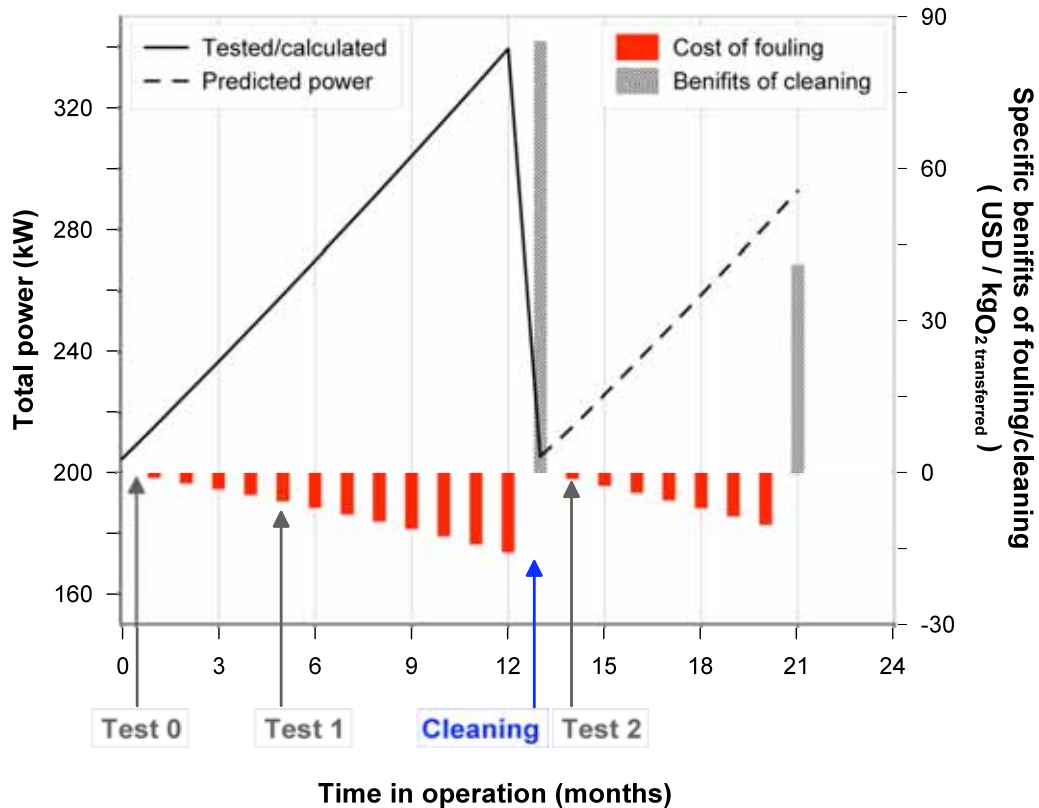
Figure 17. Energy expenditure of aeration cost. Total power consumption is calculated by the off-gas test results, which total power = initial power + power wasted. Costs and benefits are calculated based upon the power wasted. The power cost is 0.15USD/kWh and the results are normalized by unit mass of oxygen transferred.

3.2.4. Application of Real-Time Instrument – Operational Control for Energy Saving

In addition to the long term diffuser fouling, the real-time off-gas test provides useful information for plant operation. Figure 18 shows the oxygen requirement and oxygen transferred in the treatment system in a 24-hour cycle. The oxygen requirement calculated by influent chemical oxygen demand was considered as the input signal of the system, and the oxygen transferred was recorded as output by off-gas monitoring. The difference between the two values (the shade area) represents the wastage of oxygen supplied.

As shown in the former section, the treatment plant has an equalized basin to control the flow rate of primary effluent flowing into the aeration basin. The minimum flow and loading condition generally occurs at approximately 3:00 a.m. to 8:00 a.m., when the equalized basin is empty. As shown in Figure 6, the over-aeration occurs in this period. Based upon Equation 1, it is possible that the over-aeration is due to bacteria activities. During the minimum loading period, the bacteria consumes oxygen mainly for endogenous respiration instead of pollutant

consumption. A different plant operation strategy, i.e. changing the distribution of plant flow of equalized pumping rate and/or increase the pollutant concentration by sludge supernatant, could be designed to reduce the energy consumption.
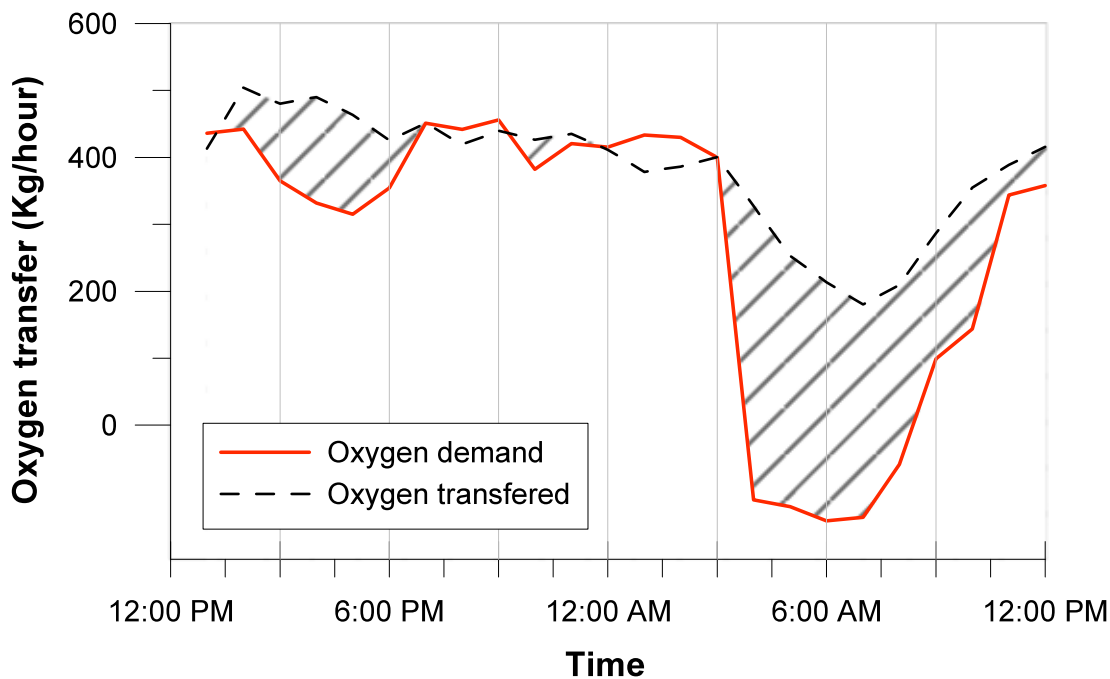
Figure18. Rates of oxygen transfer and oxygen demand of a full-scale WWTP during a 24-hour cycle. Oxygen transfer is calculated by the results of off-gas tests, and oxygen demand = CODtotal – CODsludge. The shade area represents the low loading/growing period, and the oxygen is mainly consumed for endogenous respiration but not pollutant degradation.

3.3. Automated Oxygen Transfer Monitoring System

The schematic of the automatic off-gas analyzer is shown in Figure 19. This design performs the highest simplification of off-gas measuring, hence the design maintains the same measuring accuracy as the original device (Redmon et. al., 1986). A three-way valve controlled by a time-delay relay switches the connection in time-sequence from either the off-gas or the reference air into an O_2 fuel cell, in which the air flow is driven by the off-gas itself and a lab-scale vacuum pump (300 ml/min, or 2 in. Hg). The O_2 fuel cell returns a voltage proportional to the O_2 partial pressure in the gas stream. For each measuring event, reference air and off-gas are compared, which calibrates the instrument with each measurement. The off-gas flow rate is calculated by measuring the air velocity in the air hose and recorded for each measurement to allow a flow-weighted average of the entire aeration tank. The full-scale testing campaigns produced an aeration efficiency database, which complements our previous extensive off-gas experience (Rosso et al, 2005).
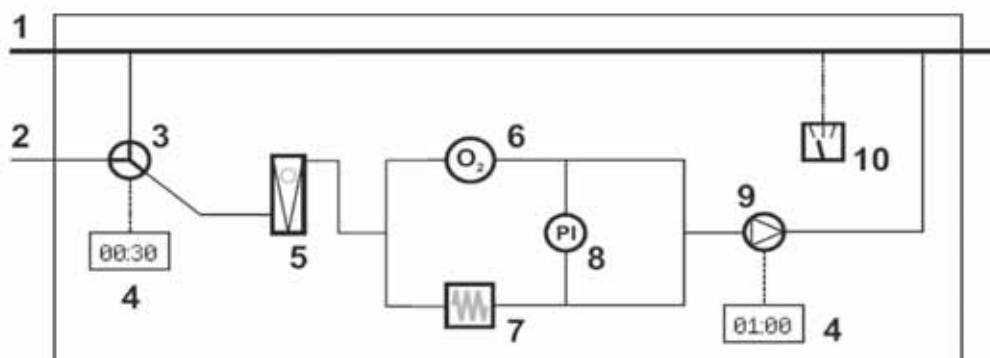
Figure 19. Schematic of the real-time automated off-gas analyzer. Key: 1) off-gas hose (from collection hood); 2) reference air intake; 3) three-way valve; 4) time delay relay; 5) flow meter (optional); 6) oxygen fuel cell; 7) resistance; 8) differential manometer; 9) vacuum pump; 10) air velocity meter. Solid lines are hydraulic lines, dashed lines are electrical connection.

3.3.1. Field-Scale Prototype 1.0

The first field-scale prototype was built as shown in Figure 20. A Teledyne oxygen meter and a Kurz flow velocity meter are still included in this device. In the later version, the Teledyne meter will be removed, and only the fuel cell will be used. Further investigation of the flow velocity sensor may also consider the removal of the Kurz flow velocity meter in our later design. In so doing, the size of the instrument will be even smaller, about half of the size shown in the picture (approximately 15"L×20"W×10"H).

Figure 20. Field-scale prototype 1.0. (Rosso and Stenstrom)

3.3.2. Field-Scale Prototype 2.0

The second field-scale prototype (2.0) built is shown in Figure 21. The layouts of air flow and electronic connection are shown in Figure 22 and 23 (two examples, one portable and the other wall-mounted, which are also presented in the appendices - Section C). In prototype 2.0, instead of using the whole Teledyne oxygen meter, this latest design uses only the fuel cell to measure the oxygen fraction in the air sample. And since the air flow velocity can be measured by the plant air flow meters, the Kurz meter is moved out from the instrument and serves as an additional and portable device. Two time-delay relays were used for system control and a NI data logger was used to record the measured signal to recorders (i.e. laptop computer) via a USB cable. The size of the new instrument is reduced to about half of the prototype 1.0.

Figure 21. Prototype 2.0. (Rosso and Stenstrom)
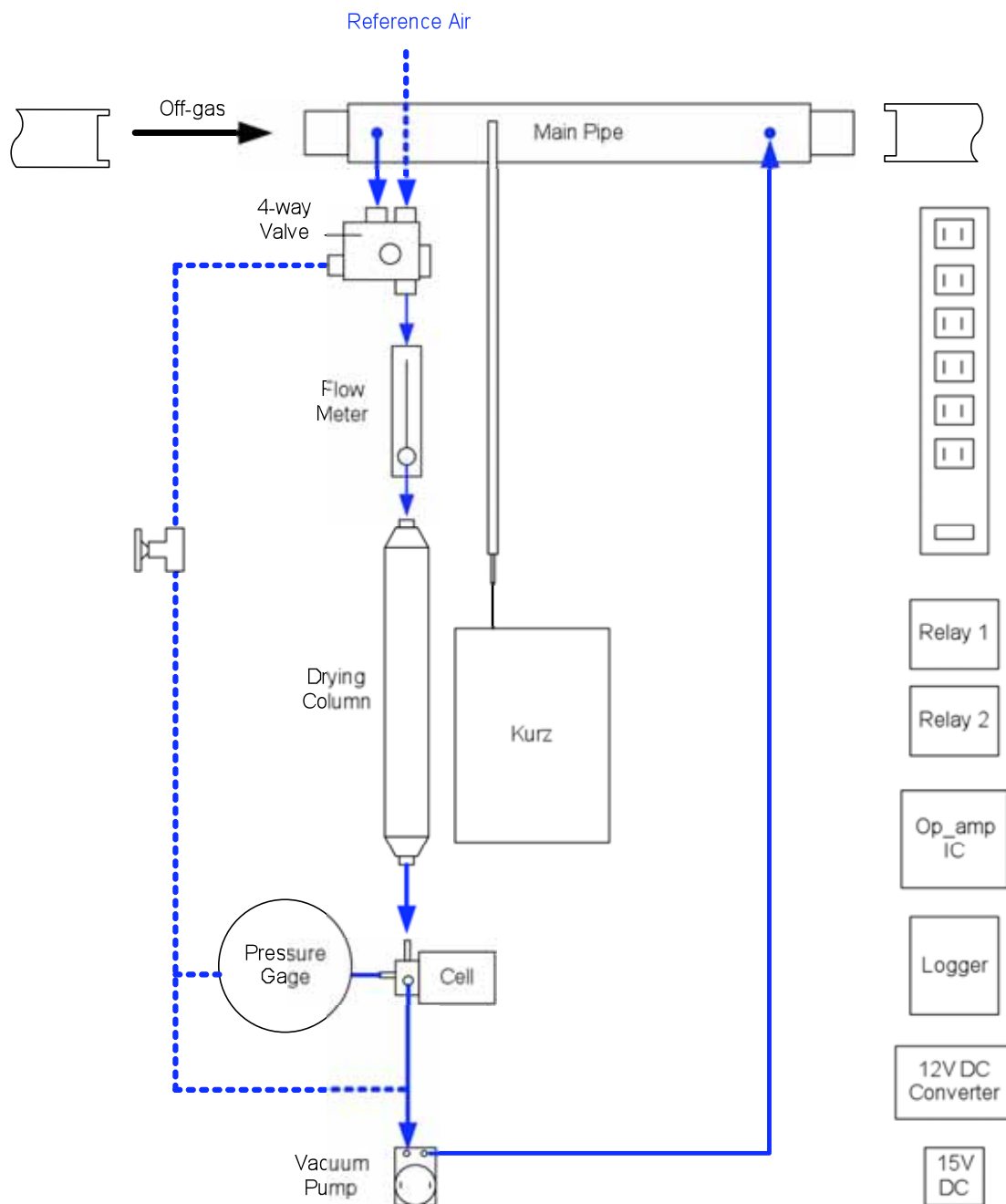
Figure 22. Air flow layout of the field-scale Prototype 2.0.
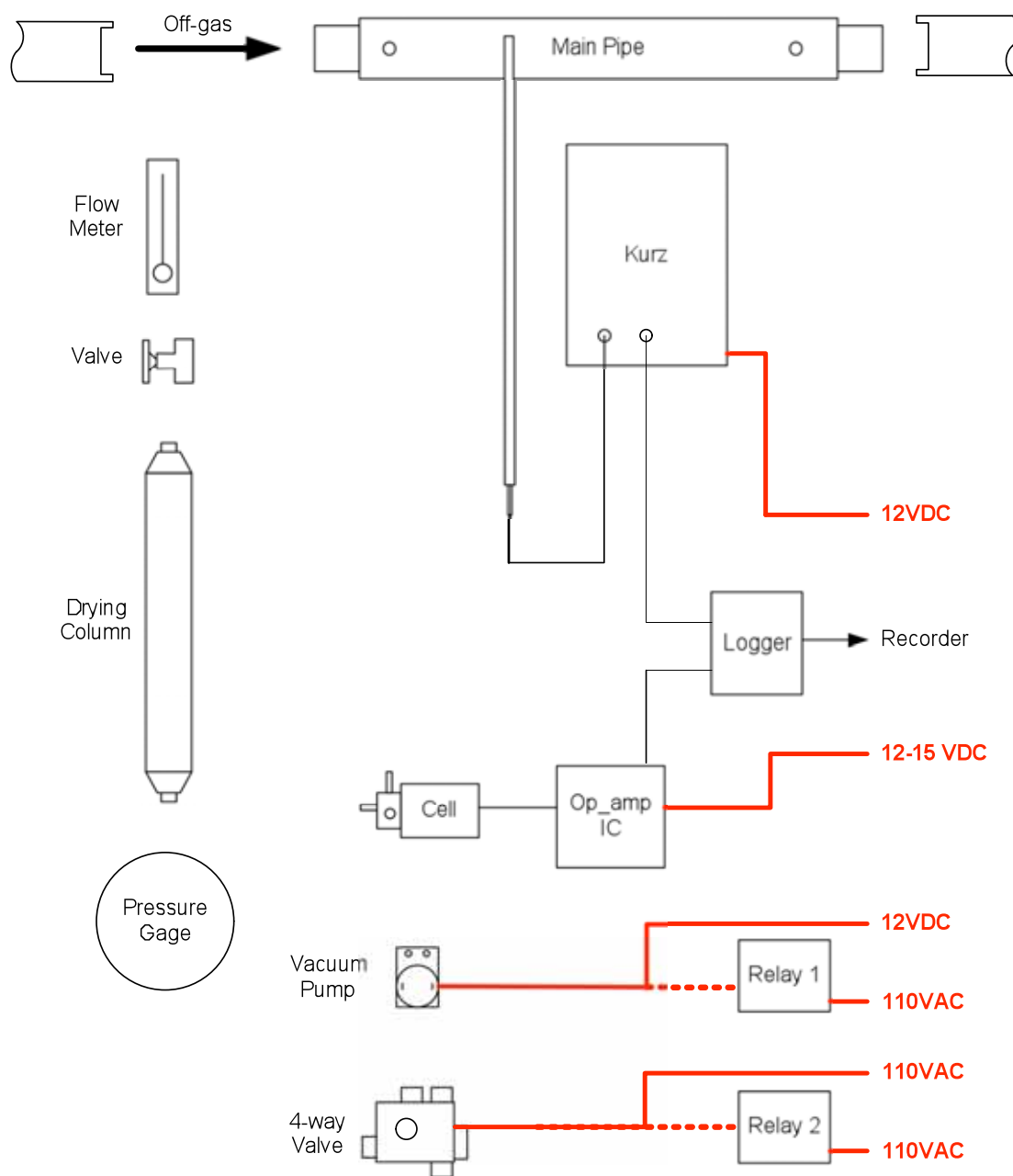
Figure 23. Layout of power connection in the field-scale Prototype 2.0.

3.4. Tests of Field-Scale Prototype

3.4.1. Lab-Scale Tests of Field-Scale Prototype

Sensitivity analysis was applied to test the field-scale prototype. The Prototype 2.0 was connected to the aeration column shown in Figure 12, and clean water tests proceeded to test the interferences caused by the running apparatus to the measurement results.

Figure 24 (a) shows the results of a classic clean water test with only the oxygen fuel cell and op-amp signal amplifier turned on (called test 1). The oxygen recovery curve shows a similar pattern as shown in Figure 13, where the oxygen fraction in air bubbles declines immediately after the sequestration of DO in process water, then recovers as an exponential function of time. Since the driving force of air flow is from the air bubbles only, the measurement data are steady and show minimal noise.

Figure 24 (b) shows the results after the vacuum pump was turned on (Test 2). The measured signal shows a much shorter response time when compared to test 1, however additionally significant noises were observed as well, possibly due to the unsteady pumping rate of the vacuum pump. The values of measurement readings are higher than in Test 1, which can be explained by the total pressure change in the system (i.e., when the total pressure is higher, the partial pressure is linearly biased as a higher measurement).

To reduce the noise, the off-gas sample must be compared with an ambient air sample. Figure 24 (c) shows the experiment results with the vacuum pump running and influent air flow switched for a 30 second interval between off-gas sample and reference (air). As a result, noise was significantly reduced and the instrument could be easily calibrated by comparing to the reference values. However, similar to Test 2, the data measured in this test have a much higher average and a continuously increasing value. It could be due to the vacuum pumping in the system. In the laboratory, the air flow in the aeration column is adjusted to the minimum amount necessary to produce enough oxygen reduction in air bubbles. Therefore the air rate in the analyzer provided by the vacuum pump may be higher than the total off-gas flow rate, thus causing the increase of fuel cell readings. In the field, the off-gas flow rate is recommended to be much higher than the pumping rate to avoid the bias formation.

(a)

(b)

(c)
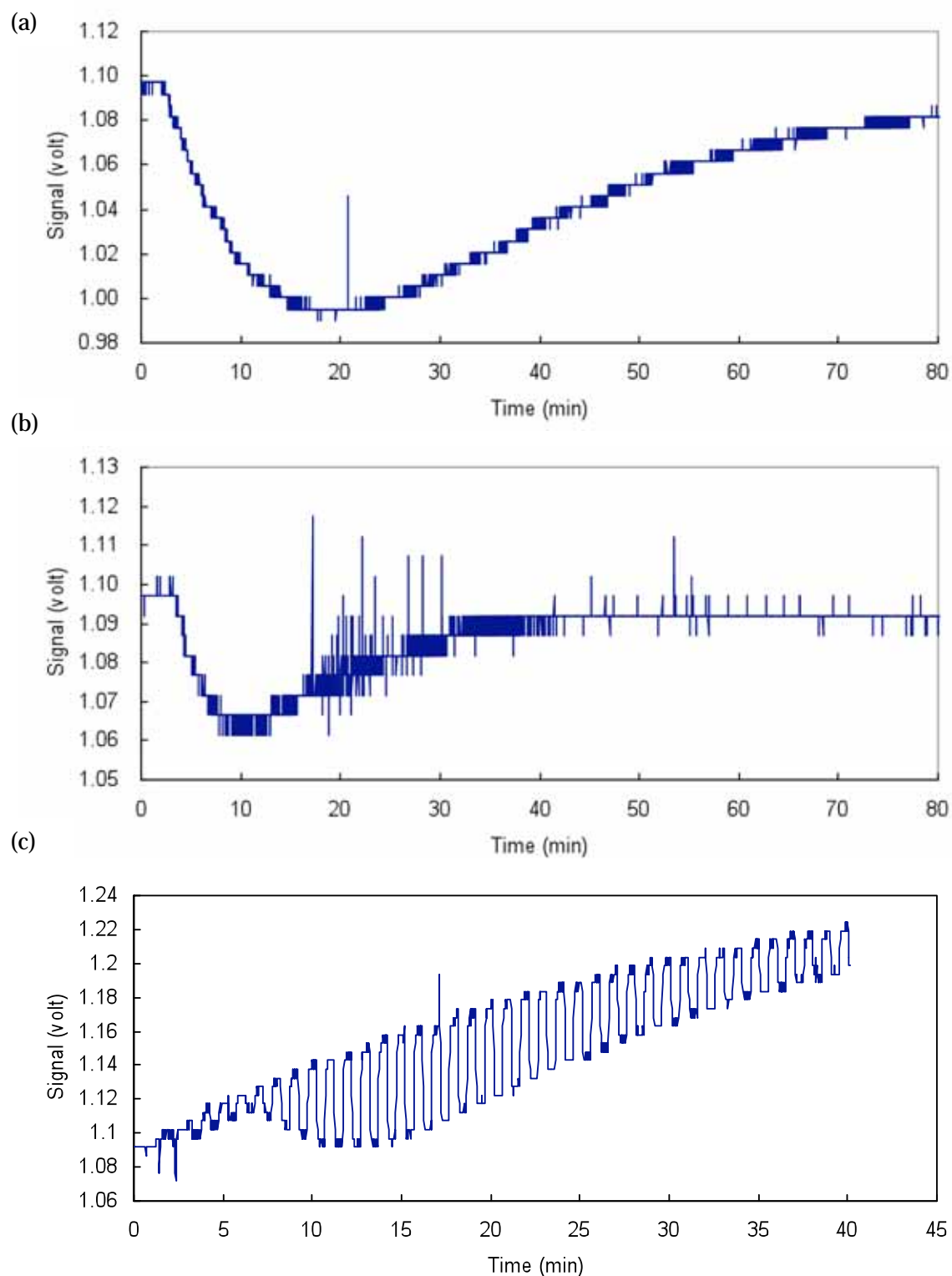
Figure 24. Lab experiment of field-scale prototype: (a) clean water off-gas test with no vacuum pump; (b) clean water off-gas test with vacuum pump; (c) clean water off-gas test with 4-way valve, time-delay relay, and vacuum pump.

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3.4.2. Field Experiments of Field-Scale Prototype

Figure 25 shows the signals recorded by the automatic analyzer in the selected WWTP. The plot contains both processed and unprocessed data (before noise filtering). The processed data have a step-pattern with a duration period of two minutes due to the alternating sequence of reference air and off-gas measurements (two + two minutes = four minutes per full measurement). As expected, the off-gas readings always have a lower value than reference air, and the difference of the two readings is proportional to the oxygen transferred.
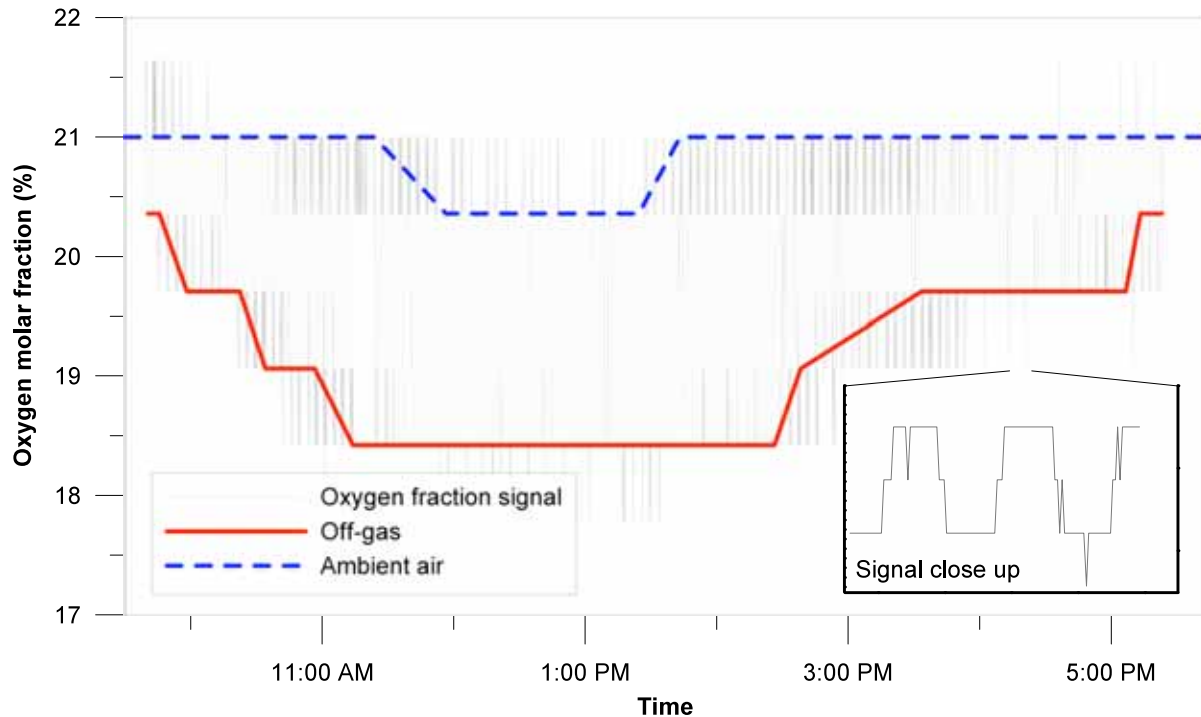
Figure 25. Continuous measurement record with the automated off-gas analyzer. The OTE is measured by comparing the difference of oxygen molar fraction (%) between reference and off-gas.

3.5. Hood Size Analysis

The hood dimensions are important when performing off-gas analysis. The area under the hood must be representative of the entire area of the tank. For fine-pore aeration systems, such as discs or domes, the spacing among diffusers should be less than several ft, but for coarse bubble diffusers or tanks that use diffusers to create strong mixing currents (i.e., spiral roll, cross roll), diffusers should be located more than 10 ft apart. Each portion of the tank area must be a sampled representative of the entire area, so hood positions must include both areas of low air-flux (air flow per unit area of tank surface) and high air-flux.

To reduce the number of separate analyses, a larger hood should be used to integrate both high- and low-flux areas of the tank. Hoods that are 10 ft by 3 ft or 8 ft by 4 ft in dimensions are common, but the specific size could be site-specific. In extreme cases, it is possible to construct a hood to cover an entire tank (Boyle, *et al.*, 1989).

A small-size hood was also tested in the field experiment. The surface area of the small hood is approximately 32 in long and 16 in wide. Comparing with the classic hood (3 ft by 10 ft, approximately 100 pounds in weight), the small hood has the benefit of maneuverability. As shown in Figure 26, a single operator can measure the OTE at any spot of the aeration tank by moving the hood and the data could be easily recorded by the off-gas analyzer and a laptop. The only pitfall of the small hood is that it might not be able to cover the whole air plume generated by a diffuser, thus the OTE reading would not be steady unless it came from a long-term integration of measured data. It is recommended that the sensitivity analysis of hood size be performed on a site-specific base.

Figure 26. Real-time off-gas test with field Prototype No. 2 and a small hood. (Rosso and Stenstrom)

3.6. Off-Gas Tests in California

This section presents several case studies of energy savings at selected WWTPs in California that are based on the off-gas analyses. Results of off-gas studies at four sites are presented, including the treatment plants of Los Angeles at Tillman, Glendale, Simi Valley, and Orange County. Aeration costs are shown in Table 3 as kWh/million gallons (MG) wastewater treated and $/person/year. The pumping energy requirement was calculated by the adiabatic function of the blowers (Metcalf and Eddy, 2003), as a function of the total air requirement and diffuser

head loss. Power cost was assumed to be $0.15/kWh, and the pumps' field transfer efficiency was 75%.

The Tillman WWTP uses ceramic domes for aeration. Before 2000, this treatment plant was operated with conventional process, which removed only the carbonaceous pollutants, but not ammonia. Off-gas tests were performed to evaluate aeration performance before and after diffuser cleaning. As a result, approximately 100 kWh/MG wastewater treated can be saved by diffuser cleaning. The plant later upgraded the system to nitrification/denitrification (NDN) process to additionally remove nitrogenous pollutants. After the upgrade, aeration performance was significantly improved. The new process provided better OTE and required less air to oxidize the same amount of pollutants. When comparing the two processes on equal basis, an improvement of, approximately 500kWh per MG wastewater treated is achieved, or an equivalent of $2.3 to $2.9/person/year in energy cost can be saved.

Similar results were found in the Glendale treatment plant, which used the same type of aerators (ceramic domes), and the plant also upgraded the operation process from conventional to NDN. Off-gas tests were performed before and after the upgrade. Compared to the results found in Tillman, the improvement in energy consumption in Glendale is slightly lower as approximately $1.2/person/year was saved. This difference can be attributed to the size of the treatment plants and wastewater characteristics. Glendale is a smaller plant and has lower pollutant concentration (132 milligrams (mg)/Liter (L)) than Tillman (162mg/L).

At the Simi Valley treatment plant, off-gas tests were performed after the system was upgraded to NDN process. This plant uses strip-type membrane diffusers for aeration and has three polishing tanks connected to four new regular process tanks (a most unique design). The function of the polishing tanks is to guarantee a consistent effluent quality, e.g. when the treatment performance is low in the process tank, extra air can be provided to the polishing tank. Due to this unique design, aeration costs in this plant were calculated as the "whole secondary treatment system", instead of each "tank" in the other cases. This plant has the lowest capital cost on aeration ($2.3/person/year) of the four WWTPs, possibly due to the two-stage aeration system. The aeration energy savings before and after diffuser cleaning is approximately 100kWh/MG wastewater treated, which is close to the results of other WWTPs.

The WWTP in Orange County uses a disk-type diffuser made of ethylene propylene diene monomer rubber. This plant has not yet been upgraded to remove ammonia due to overloading, i.e. more volumetric flow than designed capacity. In this plant, most of the fine-pore diffusers in the aeration systems (8 in 10 of the tanks) have not been cleaned since the installation of the diffusers (8 years, from 1997 to 2005). Therefore, the diffusers collected from the system were completely fouled (detail study see the membrane test in § 3.1.1), and performed poorly (i.e. low OTE, high DWP and air flux) in aeration. Based on the off-gas analysis, up to $2403/day of energy cost could be saved by diffuser cleaning.

Table 3. Summary of off-gas test results and energy saving of selected WWTPs in California

Plant	Population Served	Test Date	Process	Diffuser Condition	Required Air scfm	kWh/MG	Aeration Cost $/day	kWh/person/yr	$/person/yr
Tillman	800,000	1992/2/24	Conventional	Dirty	4296	638.2	7658	23.3	3.49
					6152	913.9	10967	33.4	5.00
		1992/6/29			7938	1179.2	14151	43.0	6.46
					6152	913.9	10967	33.4	5.00
		1993/12/10		New or Cleaned	5954	853.9	10247	31.2	4.68
					7144	1024.7	12296	37.4	5.61
		1994/7/11			4366	626.2	7515	22.9	3.43
					5160	740.1	8881	27.0	4.05
		2007/4/4	NDN	Cleaned	2628	377.0	4523	13.8	2.06
					2567	368.2	4418	13.4	2.02
					2812	403.3	4839	14.7	2.21
					2567	368.2	4418	13.4	2.02
		Average	Before Upgraded	Dirty	6135	911.3	10936	33.3	4.99
				Cleaned	5656	811.2	9735	29.6	4.44
			After Upgraded	Cleaned	2643	379.1	4550	13.8	2.08
		Upgrade savings			**3491**	**532.2**	**6386**	**19.4**	**2.91**
Glendale	220,000	1991/8/7	Conventional	New	4590	877.8	2633	29.1	4.37
					5472	1046.6	3140	34.7	5.21
					3531	675.2	2026	22.4	3.36
				Dirty	4590	909.1	2727	30.2	4.52
					4060	804.2	2413	26.7	4.00
		1992/8/3			3884	769.2	2308	25.5	3.83
					3707	734.3	2203	24.4	3.65
					5119	1014.0	3042	33.6	5.05
		2005/3/17	NDN	Dirty	4135	819.0	2457	27.2	4.08
		2007/8/16		New	3228	617.4	1852	20.5	3.07
				New	3115	595.7	1787	19.8	2.97
		Average	Before Upgraded	Dirty	4272	846.2	2539	28.1	4.21
				New	4531	866.5	2600	28.8	4.31
			After Upgraded	Dirty	4135	819.0	2457	27.2	4.08
				New	3172	606.6	1820	20.1	3.02
		Upgrade savings			**1100**	**239.6**	**719**	**7.9**	**1.19**
Simi	100,000	2005/8/4	NDN	New	5810	499.4	622	15.1	2.27

Location		Date	Type	Condition					
Valley		2006/1/11	NDN	Dirty	7107	615.9	767	18.7	2.80
		2006/9/19	NDN	Cleaned	5836	501.7	625	15.2	2.28
		Average	**Cleaning savings**		**1271**	**114.2**	**142**	**3.5**	**0.52**
		2002/10/22		Cleaned	5330	487.5	2119	17.2	2.58
					4214	385.4	1675	13.6	2.04
					6074	579.1	2517	20.4	3.06
					6446	614.5	2671	21.7	3.25
Orange County	450,000	2005/10/22	Conventional	Dirty	5454	520.0	2260	18.3	2.75
					5330	508.2	2209	17.9	2.69
					5816	503.4	6025	32.6	4.89
					6435	556.9	6666	36.0	5.41
					5816	503.4	6025	32.6	4.89
					5816	503.4	6025	32.6	4.89
			Before cleaning		5898	536.1	4300	26.5	3.98
		Average	After cleaning		4772	436.5	1897	15.4	2.31
			Cleaning savings		**1126**	**99.6**	**2403**	**11.1**	**1.67**

3.7. Air Blowers and Air Distribution Systems

Current control techniques for aeration systems are typically based on feedback signals provided by DO probes immersed in the aeration tanks. DO concentration is an effect of oxygen transfer. DO is an important indicator of proper process conditions. When the DO is too low, bacterial metabolism can be inhibited, and the sludge composition may change, reducing the treatment efficiency or even causing process failures (i.e., sludge bulking). Conversely, high DO may pose problems for denitrification zones (which require anoxic conditions), and may represent excessive energy consumption (Ferrer, 1998; Serralta et. al., 2002). Many studies have focused on improvement of the DO control system (Ferrer, 1998, Ma et. al., 2004).

In fact, most plants have blowers that can generate only limited discharge pressure before surging or overloading motors. The DWP required by fouled diffusers may be too high causing some diffusers to release no air, resulting in uneven bubble distribution throughout the tank. In other facilities, blowers may be able to discharge the DWP required by the fouled diffusers only when working outside their optimum efficiency region, resulting in increased power costs and possible damage to the blower.

To optimize the energy consumption of aeration systems, the best blower control strategy is to supply the minimum amount of process air to the wastewater treatment, yet still meeting substrate removal requirements. The adoption of a low-cost on-line off-gas measurement should be considered. Off-gas testing measures the exact mass transfer, not only an effect of it, therefore offering a new tool for accurate energy calculations. In addition, a time-series of off-gas measurements offers a tool for monitoring the decline in SOTE with diffuser fouling.

When considering blower upgrades, several factors must be taken into consideration. Redundancy must be accounted for when choosing blower units to allow scheduling shifts for operation and maintenance. In order to avoid sudden increases of AFRs (corresponding energy

demand), blowers with tuning capability are always recommended (i.e., PD blowers with VFDs, or centrifugal blowers equipped guide vanes and/or VFDs, etc.). These blower systems allow the variation of AFR within their operating range, which accommodates the variations of load in the treatment plant. When the variation is in excess of the blowers' operating range, another blower activates, as in traditional systems. The benefit of tuning systems is a smoother transition in the range of AFRs, which is reflected in an increased ease of management in terms of energy costs.

A classical problem that haunts operators and process control engineers is "hunting" that occurs with DO control systems. The basic problem is that the blower is treated as an "infinite" source by the control algorithm. The example below explains it best

A treatment plant is composed of several, parallel aeration tanks. When one tank has low DO caused by a flow imbalance or random effect, the controller calls from more air and opens an air valve, which provides more air to the affected tank. Ideally, the additional air should be provided by the blower, but in fact is not, and is robbed from an adjacent tank. This occurs because of pressure drops in the air distribution system as well as the nature of the blower. The loss of air in the adjacent tank causes the DO to drop, and the controller calls for even more air, which robs air from other tanks. Eventually all tanks are calling for more air and the control system finally responds by turning on an additional blower. Because the blowers have predefined ranges of flow and no continuous distribution of flow rates, the air to all tanks increases and the DOs begin to increase. One tank will be first to obtain excessively high DO and the control system will reduce air flow, which does not reduce blower output, but only forces more air into other tanks. Very quickly, all tanks begin to have excessive DO, and the control system finally turns off the additional blower. Now the cycle starts over again and the DOs will decline until the blower is turned back, when all tanks will yet again begin to have excessive DO.

The impact of "hunting" is excessive energy consumption caused by the starting and stopping of blower motors as well as increased wear and tear on the blowers. In cases where the operators become concerned about the impact on plant performance, they may disable the DO control system altogether and over- or under-aeration occurs. Usually the operators elect for over-aeration to avoid violating their effluent permit.

To solve this problem, several changes are needed. The first is to provide flexibility with the blowers by giving them larger "turn-up" and "turn-down" capability. The second change is a control system that is "smart" and does not consider the blower as an infinite source. This will require the control system to be equipped with a model for the blower (essentially the flow versus pressure curve and a time lag) that can be solved for each new state, so that the new system pressure can be predicted and the air valves on all tanks can be adjusted appropriately. The more challenging part of the problem is providing blower flexibility. A report covering blowers is located in Appendix III.

4.0 Conclusions and Recommendations

4.1. Conclusions

Wastewater treatment amounts to 3% of the energy consumption in California. Wastewater aeration is the most energy intensive process in wastewater treatment, accounting for 45–75% of the total energy cost for treatment. Due to the SCE's commitment to reduce 1 billion kWh/yr in its service territory, there is a clear incentive to minimize energy consumption for wastewater treatment. Therefore, aeration is the first operation to be studied and optimized for the wastewater industry.

Existing control systems do not measure energy efficiency as an operating parameter. This study designed, built, and tested successfully a fully-automated real-time aeration efficiency monitoring analyzer at several facilities. The results of this technological advancement exceeded the project goal of measuring aeration efficiency. A low-cost prototype analyzer was developed and tested successfully at a cost of $3,000–5,000 each that would operate in a fully-automatic mode without the need for supervision or operator training.

The analyzer built in this project measures the actual aeration efficiency and gives plant operators a real-time measurement (i.e., not just an estimate) of the energy required to perform wastewater aeration. This means that aeration can be optimized in real-time mode and will always be performed at the minimum energy cost.

Energy consumed by the wastewater industry in California is estimated at about 2 billion kWh/yr. Assuming market penetration of 50% and an average efficiency improvement of 15%, the large-scale implementation of aeration efficiency monitoring will allow energy savings in the range of 50–100 million kWh/yr.

4.2. Commercialization Potential

All treatment plants in California and elsewhere should be equipped with energy efficiency monitoring devices as shown in this study. The aeration efficiency monitoring analyzer as developed is relatively inexpensive and has a payback period of a few months to a year depending on plant size and energy savings achieved. There are no financial hurdles to overcome for the installation of these analyzers because potential energy savings far outweigh the analyzer's cost.

New designs and upgrades of existing facilities should include aeration efficiency monitoring as part of the design plan and the process control strategy. Therefore, the potential for commercialization is sustainable in the future if this technology is embedded in the wastewater industry as an essential component for optimized operations.

The commercialization potential for this technology goes beyond California, and a market will establish throughout the United States and abroad.

4.3. Recommendations

Implement aeration efficiency monitoring with rebate incentives, if necessary, to every WWTP. This means transferring the aeration efficiency monitoring analyzer developed in this project to every existing treatment facility that uses fine-bubble aeration. New designs of WWTPs should also include this analyzer in the control system, thereby minimizing the energy expenditure from the first day in operation on.

Power utilities, such as SCE and others, should establish a rebate program based on the energy efficiency measurements performed before and after the installation of this device for all WWTPs that use aeration.

4.4. Benefits to California

The benefits already enjoyed by Californians during the course of this project are several. Five treatment plants in Northern and Southern California were tested and have already adopted corrective measures to minimize energy losses. Moreover, the testing campaign, combined with conference presentations, gave this project valuable exposure to the wastewater industry. The outcomes of this project were presented at the California Water Environmental Association Conference in Ontario, California in March 2007, at the International Water Association Efficient Use and Management of Urban Water Supply Conference in Jeju, Korea in May 2007, at the International Water Association 4th Leading-Edge Conference on Water and Wastewater Technologies Conference in Singapore in June 2007, and were featured as at keynote lecture at the Consortium for Energy Efficiency Workshop in Long Beach, California in January 2007. Several individuals belonging to organizations outside California have approached the project team, inquiring about the availability of the analyzer and volunteering their facilities for further testing. The Consortium for Energy Efficiency offered to support the technology transfer by distributing all the information regarding this analyzer to their subscribers nationwide.

After the project is completed and the aeration efficiency analyzer is commercially distributed throughout California, there will be a clear advantage for California to set the standard for energy efficiency for wastewater treatment. Moreover, there is a potential opportunity for California businesses to take part in the following phase of the project, i.e. manufacturing and distribution of the analyzer to the wastewater industry. Furthermore, and most importantly, the large-scale implementation of aeration efficiency monitoring will allow energy savings potentially in the range of 100–150 million kWh/yr in California.

5.0 References

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6.0 Glossary

AFR	air-flow rate
ASP	activated sludge process
C-COD	carbonaceous chemical oxygen demand
DO	dissolved oxygen (mg/L)
DWP	dynamic wet pressure (inch of water)
Energy Commission	California Energy Commission
ft	feet
Hg	mercury
in.	inches
kWh	kilowatt-hour
L	liter
LRP	Lighting Research Program
M	meter
MCRT	mean cell residence time
MG	million gallons
mg	milligrams
MGD	million gallons per day
ml	milliliter
MLE	Modified Ludzack-Ettinger
NDN	nitrification/denitrification
OTE	oxygen transfer efficiency
OTR	oxygen transfer rate
PAC	Program Advisory Committee
PIER	Public Interest Energy Research
PD	positive displacement
RD&D	research, development, and demonstration
SCE	Southern California Edison
SOTE	standardized OTE

USD	United States Dollars
VFD	variable frequency drive
WWTP	wastewater treatment plant
a	alpha factor, a factor used to quantify the effect of contamination to oxygen transfer

Appendices

Project Advisory Committee (PAC) meeting minutes

Technology Assessment Report

Blower Assessment Report

Market Assessment Report

Technology Transfer Information

Technical Papers